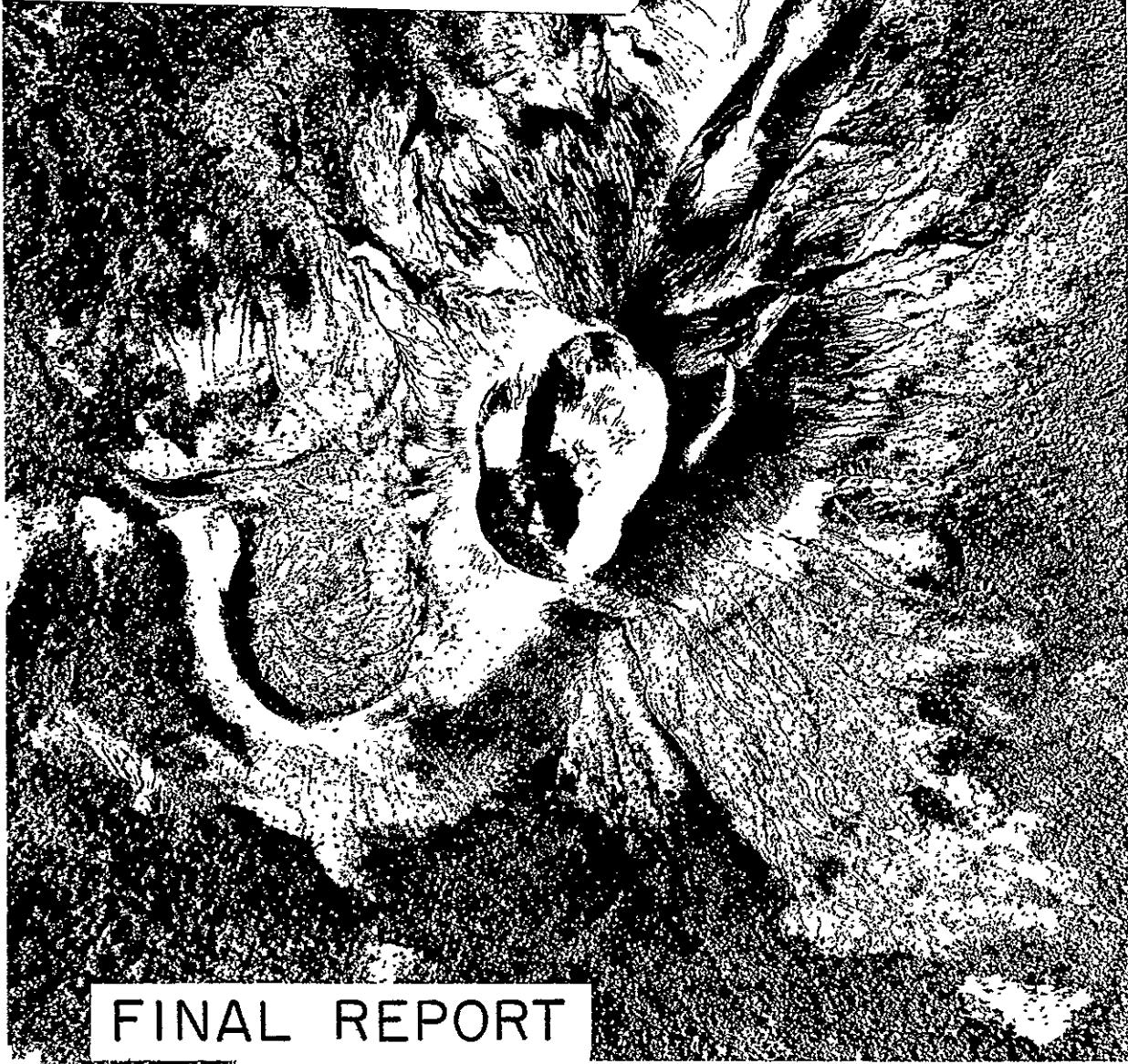


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(E76-10132) AN INVESTIGATION OF THERMAL
ANOMALIES IN THE CENTRAL AMERICAN VOLCANIC
CHAIN AND EVALUATION OF THE UTILITY OF
THERMAL ANOMALY MONITORING IN THE PREDICTION
OF VOLCANIC ERUPTIONS Final Report

N76-16554
HC \$5.00
Unclassified
G3/43 00132



FINAL REPORT

NASA Contract NAS-9-1331

July 1975

Richard E. Stoiber
Dartmouth College
Hanover, N.H. 03755

William I. Rose Jr.
Michigan Technological University
Houghton, Michigan 49931

Cover Photo:

The Nicaraguan Government supplied the cover photograph, taken over Telica Volcano on 28 December 1963.

FINAL REPORT

CONTRACT NAS - 9-13311 (EPN 596)

An investigation of thermal anomalies in the Central American volcanic chain and evaluation of the utility of thermal anomaly monitoring in the prediction of volcanic eruptions.

July 1975

Contents:

Original photography may be purchased from
EROS Data Center
10th and Dakota Avenue
Sioux Falls, SD 57198

Summary Statements
Technical Results:

- A. Structural Geologic Mapping
- B. Cooling of Izalco Volcano
- C. April 1973 Nuée ardente at Santiaguito volcano
- D. September 1973 Nuée ardente at Santiaguito

Richard E. Stoiber
Department of Earth Sciences
Dartmouth College
Hanover, N.H. 03755

William I. Rose, Jr.
Department of Geology and Geological Engineering
Michigan Technological University
Houghton, Michigan 49931

SUMMARY STATEMENTS

Original Objectives:

The stated purpose of this research was not accomplished. We intended to investigate thermal anomalies in the Central American volcanic chain (Figure 1) and to evaluate the utility of thermal anomaly monitoring in the prediction of volcanic eruptions. Our goals were not achieved because crew schedules and weather precluded predawn imagery.

Summary of Accomplishments:

Ground truth data collection which is given in our progress reports proves that significant anomalies exist at 13 volcanoes within the test site (Table 1). The dimensions and temperature contrast of these ten anomalies are large enough to be detected by the Skylab S192 instrument. (Table 2). Further, we know that the dimensions and intensity of thermal anomalies have changed at most of these volcanoes during the Skylab mission. These changes would also have been detected by repetitive imagery. In summary, our proposed plan would have provided a good test of repetitive thermal anomaly monitoring of volcanoes. The test area was ideal, containing many hot volcanic areas. The one year duration was long enough to ensure changes in these anomalies.. The plan could be followed again as a new experiment with only minor modification.

We monitored volcanic activity during the Skylab mission. Two of the attached reports describe significant activity events

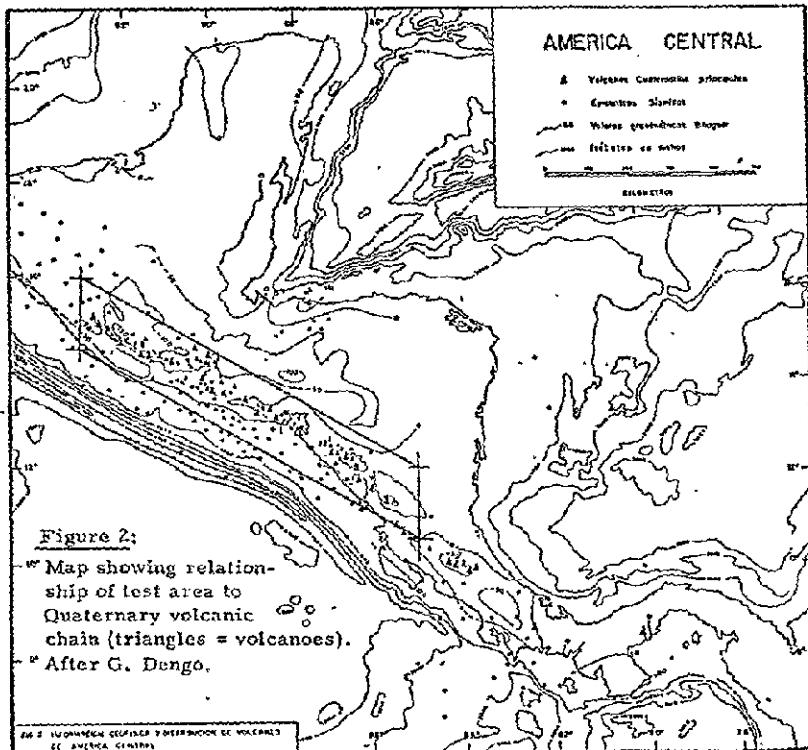
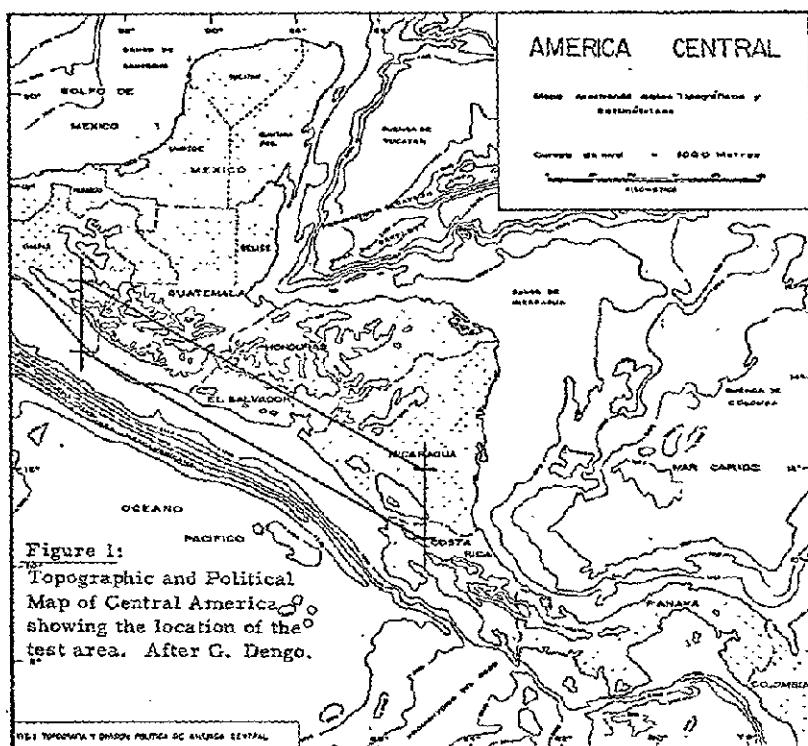


FIGURE 1

TABLE 1
Volcano-thermal anomalies within the test site

<u>Volcano</u>	<u>Location</u>	<u>Nature of anomaly(s)</u>
Santiaguito	14°45.5'N 91°32.9'W	Several anomalies with varying sizes and intensities
Fuego	14°28.9'N 90°52.9'W	Summit crater and nearby fumaroles
Acatenango	14°30.2'N 90°52.4'W	Linear anomaly north of summit
Pacaya	14°23.0'N 90°36.2'W	McKenny crater and large areas SW and NW flanks
Izalco	13°48.9'N 89°38.1'W	Summit crater
Santa Ana	13°51.2'N 89°37.8'W	Crater lake and marginal fumaroles
Tecapa	13°29.8'N 89°30.2'W	Crater lake and geothermal area on NNW slope
San Miguel	13°26.2'N 89°16.3'W	Crater bottom
San Cristobal	12°42.0'N 87° 1.0'W	Central crater 1000 x 600 m
Telica	12°36'N 86°52'W	Central crater 300 x 300 m
Cerro Negro	12°31'N 86°44'W	Crater, 270 x 230 m; E. flank of cone; 1968 lava flow
Momotombo	12°25'N 86°33'W	Crater NE of summit, fumaroles at SW base
Masaya	11°57'N 86° 9'W	Lava lake in crater 300 x 300 m

More details on anomalies can be found in our progress reports.

TABLE 2
Selected Examples of Central American
Volcano-Thermal Anomalies

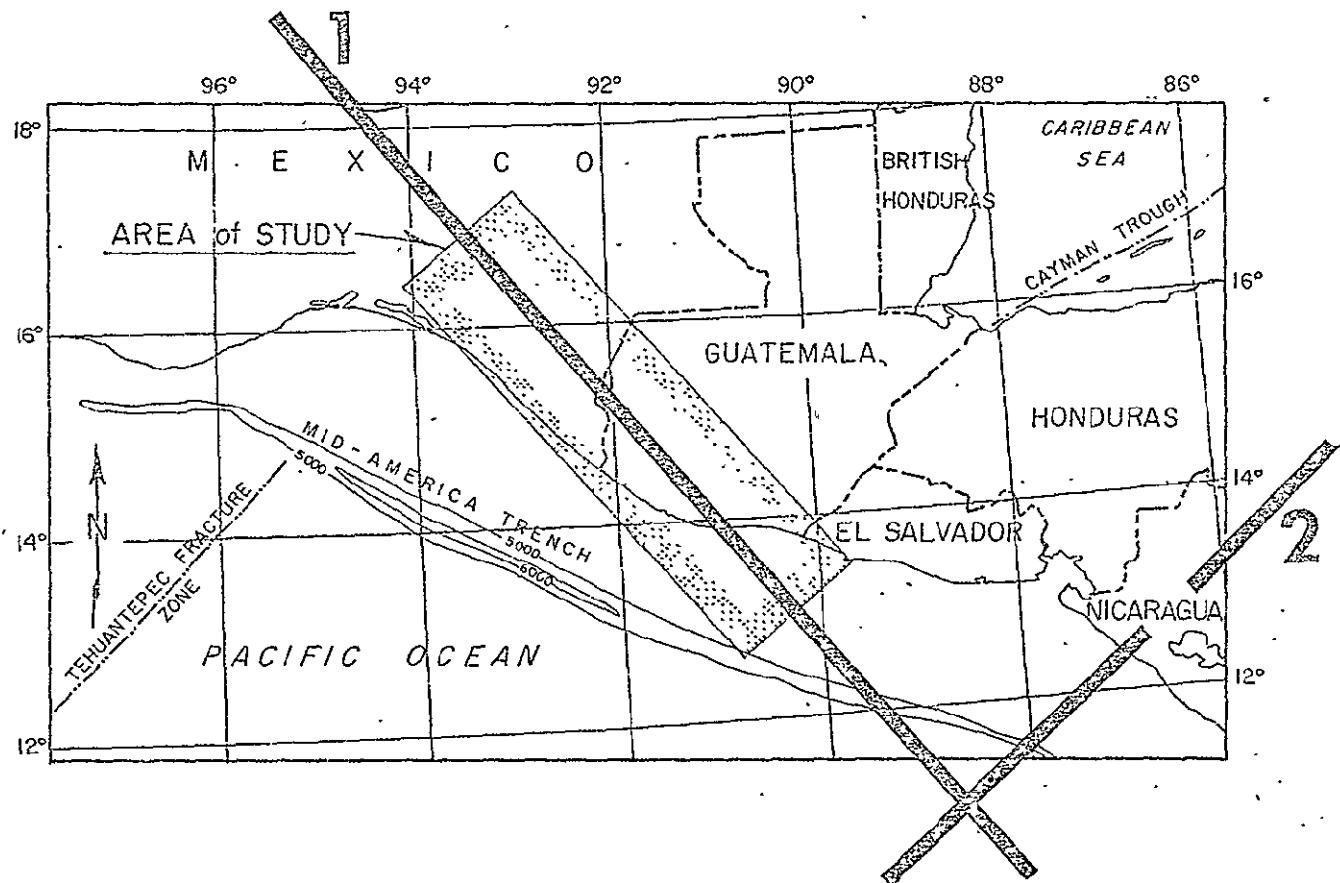
<u>Specific Examples</u>	<u>d, m</u>	<u>T, °K</u>	<u>Change During Mission</u>
Izalco	125 x 125	2°-8°	Seasonal ups and downs
Pacaya (Oct.-Dec. 1972)	100 x 1500	>20°	Steady size increase
Santiaguito (Brujo)	200 x 1500	>10°	Steady 100% size increase
Santiaguito (Caliente)	1000 x 1000	>10°	Steady 5° cooling

(C, D), and one describes repetitive ground thermal surveys (B).

The Skylab SL90 photographs supplied us as support for the thermal work were excellent for structural geologic studies (A) and provide new information on an area in which there was little geologic knowledge. We have made the results of our work known to many geologists with active interests in Southern Mexico and Guatemala and we are confident that our new map will provoke increased interest in the geology of this region. Thus ground investigations will be accelerated and better focused.

Table 3
S190 Photography over the test area.

<u>No.</u>	<u>Date</u>	<u>Ground Track</u>	<u>Notes</u>
SL-3-25-70-82	September 73	1	190A
SL-3-84-27-34	September 73	1	190B
SL-4-90-339-348	February 74	1	190B
SL-4-4B-104-116	February 74	1	190A
SL-4-94-296-303	February 74	1	190B
SL-4-66-142-145	February 74	2	190A



TECHNICAL RESULTS

A. Skylab photography applied to geologic mapping
in Northwestern Central America by W. I. Rose, Jr.,
D. J. Johnson, G. A. Hahn and G. W. Johns

Publication of the report:

1. Proceedings of Earth Resources Survey Symposium,
NASA-JSC, Houston, Texas, June 1975 (in press).
2. Trans. Amer. Geophys. Un., v. 56, p. 347 (1975).

SKYLAB PHOTOGRAPHY APPLIED TO GEOLOGIC MAPPING IN NORTHWESTERN CENTRAL AMERICA

By W. I. Rose, Jr., D. J. Johnson, G. A. Hahn, and G. W. Johns,
Michigan Technological University, Houghton, Michigan

ABSTRACT

Two photolineation maps of southwestern Guatemala and Chiapas have been made from S190 photographs along a ground track from Acajutla, El Salvador to San Cristobal de las Casas, Mexico. The maps document a great structural complexity spanning the presumed triple junction of the Cocos, Americas and Caribbean plates. The Polochic fault zone, supposedly the Americas-Caribbean plate boundary, is a sharply delineated feature across western Guatemala. Westward of the Mexican border it splayes into a large number of faults with NW to SW trends. The structural pattern is quite different to the north (Americas plate) and to the south (Caribbean plate) of the Polochic fault, though both areas are dominated by NW-trending lineations.

Within the Central American volcanic chain the lineation patterns support the segmented model of the Benioff Zone, by showing a concentration of transverse lineations in the predicted locations, most notably NE-trending elements near Quezaltenango, Guatemala. Compilation of circular and arcuate lineations within the Guatemalan Highlands offers new information about the nature and distribution of Early Quaternary and Tertiary volcanic vents.

The structural pattern obtained from the new maps are compared to patterns described on recently published maps of more southerly parts of Central America, to begin a synthesis of the structure of the convergent plate boundary.

INTRODUCTION

In this study a series of Skylab S190A and S190B photographs taken in February 1973, along a northwest-trending ground track extending from Acajutla, El Salvador to San Cristobal de las Casas, Mexico (Figure 1), have been interpreted for geologic structures and other features. The area is about 150 by 500 km, and is of particular interest for two reasons. First it crosses the presumed Americas-Caribbean plate boundary, which is thought to be marked by the Polochic fault, at a point near the triple junction of these plates with the underthrusting Cocos Plate. The dramatic expression of the Caribbean-Americas plate boundary traversing Guatemala has been already shown in Skylab imagery by Muehlberger and Ritchie (1975). Secondly, this area has not been mapped in detail, and so structural information was very limited. Thus, the possibility of producing a useful geologic contribution was enhanced.

Recently several new geologic maps of parts of Central America have been published (Bonis, et al., 1970; Carr, 1974; Anderson, et al., 1973; Wiesemann, 1974; Martinez, 1973). The area mapped in this study complements these other maps to provide more detailed structural patterns along the Central

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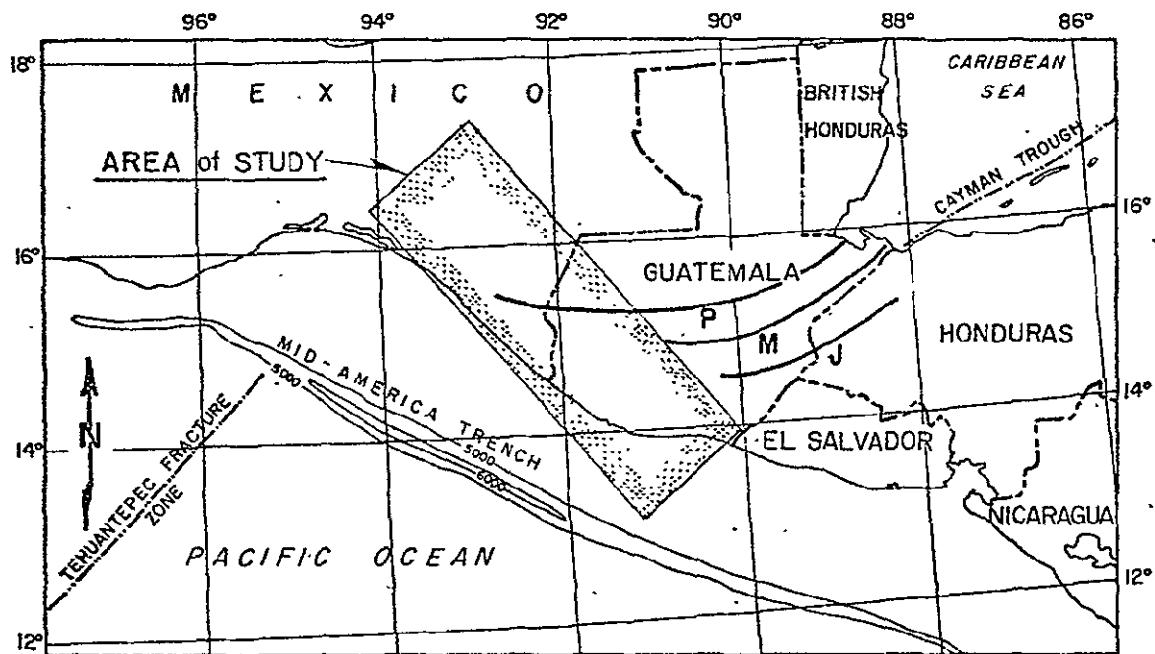


Figure 1: Map showing location of area mapped in Figure 2. Lines labeled P, M and J are the approximate locations of the Polochic, Motagua and Jocotán fault systems, respectively.

American Pacific Coast from Chiapas to Costa Rica.

The existence of new data allows reflection upon several previous structural interpretations of Central America (Dengo, et al., 1970; Kesler, 1971; Malfait and Dinkelmann, 1972; Stoiber and Carr, 1973).

METHODS

The photographs used in constructing the maps were chiefly of three types, all from the S190 camera system. Aerial color photographs were used most extensively. These were judged particularly effective for mapping during the Central American dry season, when much of the foliage is absent. The best set of images we had to study were taken in February 1974 (SL4 RL4B FEB74 102-113). Another excellent set of photographs along a nearly identical ground track is available for September 1973. Because of the dry season timing and because of better cloud conditions, we selected the February 1974 photographs. Black and white infrared and color infrared photos taken simultaneously proved useful for special purposes in our mapping and were used supplemental to the aerial color photographs. The infrared photos did not show any lineations not observed in the other photographs. High resolution aerial color (S190B) pictures were used exclusively in one of the maps (Figure 5).

All photographs were studied as stereoscopic pairs, this approach greatly enhancing many of the structures mapped.

The first new map produced is a compilation of photolineations and miscellaneous other geologic features (Figure 2). A total of 786 photolineations were mapped, with 3/4 of these lying to the north of the Polochic fault zone. Except for the detailed work of Anderson, et al. (1973), previous maps have shown a low fault density in the studied area, a fact more attributable to the reconnaissance nature of the mapping than to structural simplicity.

The map has three weights of lines. Heavy solid lines correspond to lineations that have great topographic expression. The Polochic fault is the longest of these, and shows up to 1500 m of topographic expression. Other heavy lines correspond to scarps and linear river valleys. Thinner solid lines represent lineations that are readily observable (i.e. reproducible by a second interpreter), but judged less prominent than the major set. Dashed lines represent mapped lineations that are most subject to personal interpretation. All of the lineations were scrutinized for possible non-geologic origin and some lineations were rejected on these grounds. High resolution photographs (S190B) were useful in demonstrating cultural or vegetational lineations. Thus we believe a high percentage of the mapped features have real geologic significance, and together represent the structural pattern of the area.

The cloud cover over the map area varies from 0 to 100%. Four arbitrary divisions are made on the map (see Figure 2). Lineations drawn in cloud covered areas were drawn with extreme care; no lineations could be drawn in areas with heavy cloud cover. Thus, some lineations that terminate at cloud cover boundaries on the map probably continue.

Figure 2: Photolineation map of a portion of southern Mexico and southwestern Guatemala.

INTERPRETATION

The Plate Boundary and the Polochic Fault Zone

The Polochic fault (name taken to include the Cuilco-Chixoy-Polochic system of faults) is the single dominant structural feature of the area. The fault does not obviously extend westward beyond the Sierra Madre Mountains with the clear identity it shows to the east. This observation was made prior to study with satellite photography (Kesler, 1972). From the new map, it seems likely that movement along this plate boundary becomes more complex, and is absorbed in a "horsetail" system of mainly parallel E-W trending structures shown to the north of the Polochic trace. The break in identity of the Polochic structure occurs before the fault reaches either the cloud-covered area of the photographs or the alluvial coastal plain, so we believe that this observation is significant.

Movement along the Polochic system supposedly has a left lateral strike-slip component. In view of this, it is surprising that only one of the lineations mapped crossing this structure in Figure 2 shows left-lateral offset. At distances of 20 to 30 km north of the Polochic, some lineations appear to be bent in a left lateral sense, however. This may also support the idea that some of the strike-slip movement of the Polochic system has occurred north of the principal fault trace. Malfait and Dinkelman (1972, p. 259, 261) have proposed that an increased rate of underthrusting at the Middle America trench after the late Miocene caused compression along the Motagua and Polochic systems and thereby inhibited strike-slip movement. This would be especially effective at stopping movement to the west along these faults, since the trends of the faults curve to be more nearly perpendicular to the assumed convergence of about N30°E. Thus, it seems plausible that increased underthrusting rates have caused the left-lateral displacements, which fit the plate tectonic model in this area, to move further to the north. The previous northward progression of movement along en echelon left lateral shears is suggested by the configuration of the Jocotán-Chamelecon, Motagua and Polochic systems (Figure 1).

Muehlberger and Ritchie (1975) suggest that the Polochic fault bifurcates into NW and NE trending forks at the Sierra Madre; the NE-trending branch they believe to reflect the plate boundary. We do not wholeheartedly agree with this interpretation for several reasons: 1) The prominence of this fault is not at all comparable to the eastern extension of the Polochic. 2) We could not trace this feature across the coastal plain. 3) This fault parallels numerous other NE-trending structures that occur transverse to the volcanic chain at several places in Guatemala, and we suggest that the origin of this westernmost structure is analogous to the others, rather than having a unique explanation. Our own explanation fits concepts of segmented underthrusting which we discuss further below.

Predominance of Northwesterly Structures

We have compared the patterns of faulting of the area south of the Polochic fault to the area north of this structure. To show the general faulting patterns of both areas we constructed rose diagrams (orientation-frequency diagrams) for both these areas (Figure 2). Both rose diagrams show a predominance of northwest-trending structural elements. This direction is roughly parallel to the coastline and the offshore Middle America trench. The predominance of northwesterly faulting is a feature of Central American geology from Mexico to Panama, as shown by previous small scale map compilation (Dengo and Levy, 1970) and must be closely related to plate convergence. Though they are the dominant fault directions, we are not at all

certain of the nature of the offset along these structures. Idealized models of zones of plate convergence show that normal faulting as a result of geanticlinal uplift might parallel the offshore trench in certain situations (Dickenson, 1972). Dengo and others (1970) favor this explanation for Central America, citing the Nicaragua graben as an obvious example of the predominately normal faulting. Some or many of the NW-trending structures may be right-lateral shears, analogous to the Jalpatagua fault (Williams and others, 1964). Indeed, recent geologic mapping in Nicaragua has suggested that the Nicaragua graben may have opened with some right lateral shearing component (Williams, 1972). New evidence of this type of interpretation is becoming available from the work of Carr (1974, and in press) in southeastern Guatemala and western El Salvador.

We took advantage of the availability of new structural information along the length of Central America to begin a structural comparison along the volcanic belt (Figure 3). Rose diagrams were constructed from new geologic maps available from the work of Carr, 1974 (Area 4), Wiesemann, 1974 (Areas 5 and 6) and Martinez, 1973 (Areas 7, 8 and 9). Together the data represent a series of similar size areas from north to south (1-9). Such a comparison is meant only as a first superficial look at structural patterns and all conclusions are general and tentative.

In all but one of the areas tested (Figure 3) northwesterly faults predominate, and in all of the areas northwest-trending structures are very numerous. The parallelism of the strike of Middle America trench and the seismic zone with these structures points to a direct association. In more detail, the association is not perfect, for the more westerly ($N75^{\circ}W$) trend of the Middle America trench south of El Salvador is not accompanied by a discernible westerly shift of the northwest-trending structures in the El Salvador segments (Areas 5 and 6). We do not know the reason for this, but do not feel it negates the general association of the strike of underthrusting and the attitudes of the predominant faults along the volcanic axis.

Kesler (1971) has proposed, on the basis of structural trends in Mexico and South America, that the pre-Mesozoic structural grain in nuclear Central America trends northwesterly. We cannot say to what extent a pre-existing structural grain influences the northwesterly dominance. We are quite confident that there is no significant decrease in the relative dominance of northwesterly structures from north to south along the Central American volcanic axis. This suggests that underlying continental crust, which is known in Guatemala and unknown (and probably absent) in Nicaragua, cannot alone account for a uniform northwesterly fault concentration.

Comparing the predominately NW-trending structures of Areas 1 and 3 (Figure 3), the slightly more westerly orientation of Area 1 lineations is observed. This difference may be due to the slight differences in the interactions between the Cocos-Americas plates (Area 1) and the Cocos-Caribbean plates (Area 3). Following this speculation, if convergence of the Cocos-Americas plate is $N30^{\circ}E$, perpendicular to the predominant structural elements, then convergence of the Cocos-Caribbean plate might be indicated as slightly more nearly easterly, perhaps $N50-60^{\circ}E$.

It is very important to any real understanding of the structure of Central America (and presumably other convergent plate boundaries) that field work which better describes the significance and nature of this predominant NW-trending set of structures be completed.

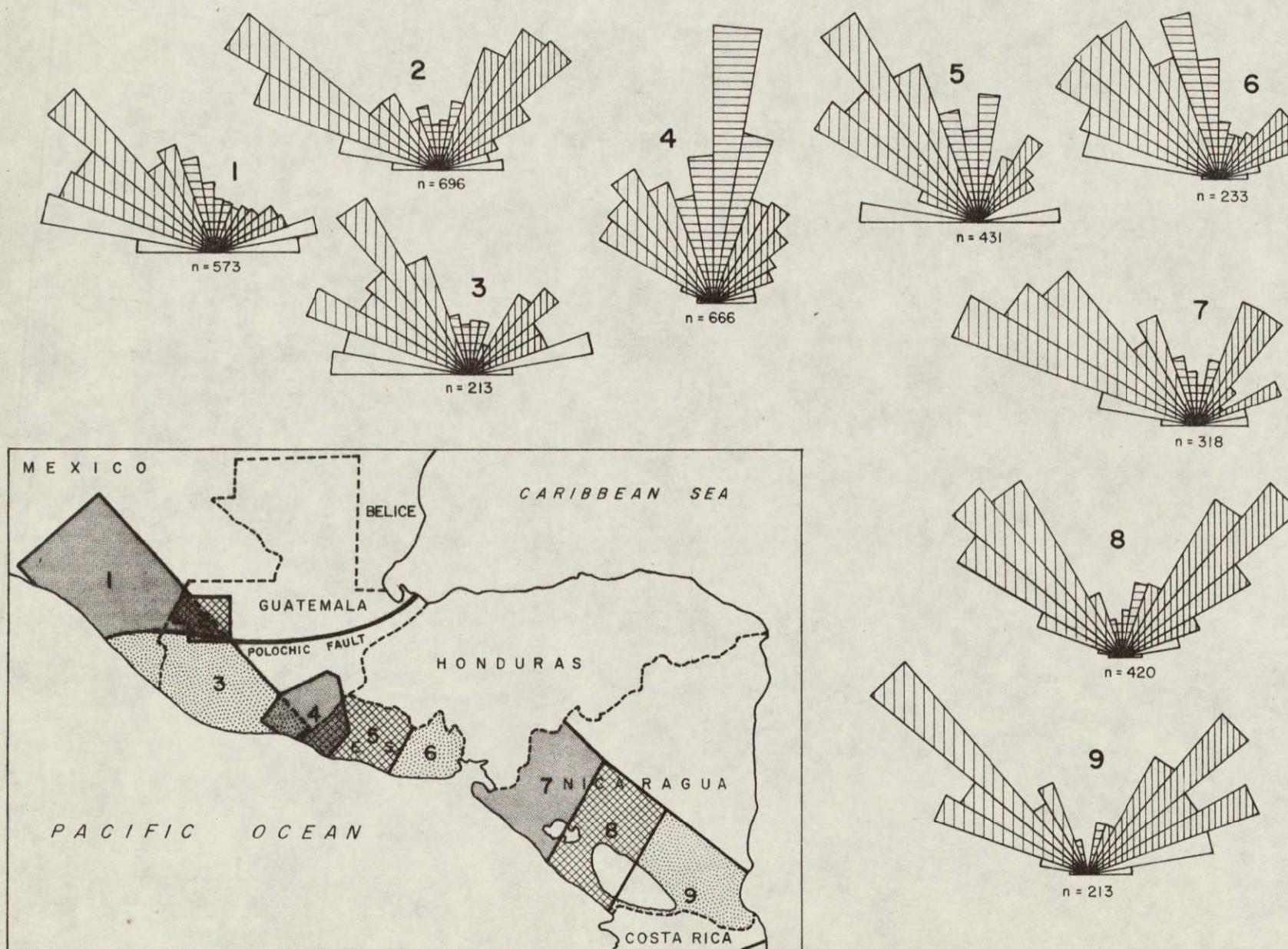


Figure 3 - Rose diagrams of structural features from along the Central American volcanic axis. Numbered rose diagrams are keyed to areas numbered on the map. Sources of data are given in the text. The number of structures on which the rose diagram is based is given under each.

"Transverse" NE Faulting

South of the Polochic fault, NE-trending faults make up a large relative proportion of structures on our photolineation map (Figure 2). The map shows that faults of this orientation are concentrated at several restricted portions of the area. The most obvious concentration of NE structures occurs at Quezaltenango, in western Guatemala, with a series of lineations paralleling the Zunil Fault. The position of this and the other NE lineation groups support the model of segmented underthrusting for Central America (Stoiber and Carr, 1973; Carr and others, 1974) since they coincide very well with the proposed discontinuities in the seismic zone. These discontinuities were originally postulated and located on the basis of differences in the strikes and positions of volcanic lineaments of the historically active volcanoes and supported by seismic data. In addition to the obvious concentration of NE lineaments at Quezaltenango, there are also suggested concentrations east of Pacaya volcano and at Tacaná volcano. The lineations appear to denote zones of about 20 km in width. The most westerly zone of transverse structures (at Tacaná) is that proposed by Muehlberger and Ritchie as the Americas-Caribbean plate boundary extension. We propose it to be analogous to the Quezaltenango and Pacaya zones, having the same strike and width, and occurring in the spot predicted by the Stoiber-Carr model. It should be noted that all three of these transverse fault zones are associated with noticeable submarine canyons offshore in Guatemala (see Stoiber and Carr, 1973, p. 306). If these transverse zones represent left-lateral shears (see below), offset along the Tacaná zone is in the same sense as the Polochic fault, and thus at least some of the plate boundary movement could be absorbed by this transverse zone, as suggested by Muelhberger and Ritchie (1975).

North of the Polochic fault NE-trending faulting is less prominent. This is shown by the rose diagrams of Figure 2. A small part of this northern section of the study area has been mapped in some detail by Anderson and others (1972). The area covered is entirely in Guatemala and is outlined as Area "2" in Figure 3. The rose diagram for Area 2 shows that NE-trending structures are a very important fraction in this area. On consulting the geologic map it is clear that these faults are generally much shorter than faults of other orientation, indeed they are generally shorter (2-4 km) than any of the photolineations mapped in Figure 2. This, we believe, explains the only notable difference in the rose diagrams of Areas 1 and 2. This does not detract from the observation that through-going northeasterly structures are more important south of the Polochic fault system.

NE-trending faults show noticeable population peaks in all but one of the areas tested (Figure 3). In general, there appears a tendency for the relative proportions of NE-trending structures to increase southward. This observation may not be significant, however. The northeasterly faults might be expected to be underrepresented in maps prepared from satellite photographs (i.e. Areas 1 and 3) because they are not as long as other faults.

On the geologic maps used in preparation of Figure 3, we cannot observe obvious concentrations of NE-trending structures within zones transverse to the volcanic axis within El Salvador and Nicaragua. This could be because 1) Such concentrations do not occur. If true, this appears to negate the support given the Stoiber-Carr model of segmented underthrusting by the new photolineation map. 2) Satellite-prepared maps, which tend to emphasize through-going structural elements, are better suited to demonstrate these concentrations. 3) Such concentrations are masked by changes in the locations of segment boundary zones during the Neogene. Alternative 2 can be tested by study of new satellite photos covering El Salvador and Nicaragua.

The proposal of left-lateral shearing along these transverse faults given by Stoiber and Carr (1973) is consistent with the plate convergence model, since as these authors show, underthrusting rates should be increasing from north to south in Central America. Segments to the south are, therefore, underthrusting continually more rapidly and their boundaries should show left-lateral shear. Dramatic recent evidence supporting this interpretation exists with the study of the pattern of faulting responsible for the Managua earthquake of December 1972 (Brown and others, 1973). Four en echelon northeast-trending faults showed clear left lateral offsets. Managua is located along one of the transverse segment boundaries proposed in the Stoiber-Carr model.

Along the Zunil Fault in western Guatemala, Johns (1975) has determined that movement is at least in part normal faulting while geophysical work has suggested left-lateral offset along parallel faults near Totonicapán, Guatemala (M. J. Whims, personal communication). M. J. Carr (in preparation) is at present completing a careful structural field study in southeastern Guatemala which should further clarify the nature of NE-trending faults.

N-S Trending Structures

Data of Figure 4 suggests that N-S trending structures are more prominent within El Salvador and Eastern Guatemala than in areas to the northwest or southeast along the volcanic axis. N-S-trending structures in these areas may be associated with grabens, such as the Guatemala City graben and the Comayagua graben. Thus, E-W extension may be especially important within Areas 4, 5, and 6. Extension along N-S features in these areas is explained by Malfait and Dinkelman (1972, pp. 259-261) by temporary pinning of southern Guatemala and western Honduras to the North American plate. The result of such pinning would be to produce the most pronounced extension exactly where it is observed. Extension could be expected to decrease to the southeast with decreased proximity to the plate boundary. It would be also expected to decrease in intensity northwestward, since the Polochic fault (representing the plate boundary) curves to a more nearly E-W orientation. Pinning of the fault would be progressively more effective to the west since the fault is more nearly perpendicular to the underthrusting. N-S extension is also compatible with the idea of NE left-lateral shearing and the association of these structural elements in the Managua area is pointed out by Stoiber and Carr (1973, p. 320-321). We can anticipate further interpretation of all of the structural elements of Area 4 (where N-S faulting is most important) from M. J. Carr (1974 and in preparation).

Relationship of Structural Patterns with Ore Deposits

In order to compare the results with the general structural synthesis, we compiled information on the attitudes of veins and fractures associated with various types of mineral deposits in Central America (Roberts and Irving, 1957). Figure 4 shows the results, and demonstrates noticeable NW and NE concentrations. This pattern correlates well with the general structural pattern defined in Figure 3.

Miscellaneous Features Observed with the Study Area

Because the photographs used were taken in the dry season, ground color was observable in most of the study area. We noticed areas of anomalously blue-grey color which seemed to correlate with serpentinite bodies along the

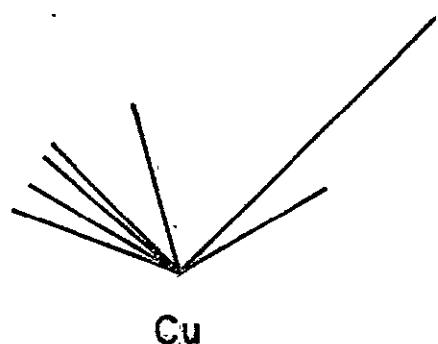
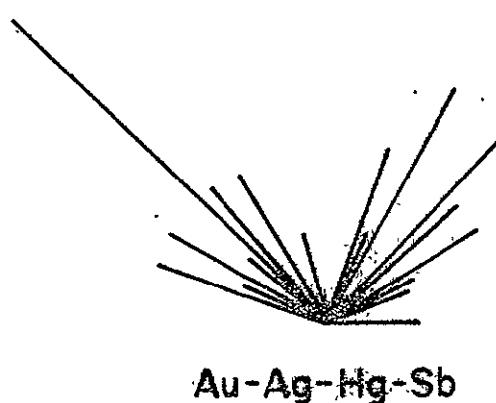
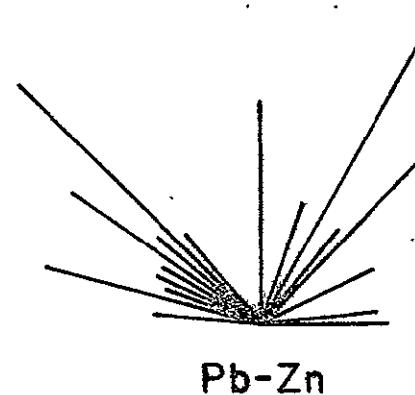


Figure 4: Rose diagrams of trends of veins and fractures associated with different types of Central American mineral deposits. Data on which the diagram is based comes from Roberts and Irving (1957). Trends of veins and fractures were plotted in 5° intervals.

Polochic fault (Figure 2). Most, but not all of these areas were previously mapped as serpentinites.

Areas of anomalously red-orange colored ground were mapped as "possible gossans" (Figure 2). Field examination would be necessary to verify the cause of abnormal coloration.

In the northwestern part of the map area, the outlines of several small possible intrusive bodies are shown. These are delineated based on topographic, geomorphologic and coloration criteria. Again, these features await field verification.

Large lobate geologic units are delineated on infrared photographs on the Guatemalan coastal plain south of Guatemala City and Cuilapa (see Figure 2). The explanation of these features is still unknown, but geologic mapping by University of Missouri geologists headed by D. K. Davies is now in progress. Infrared photography shows these units as diffuse dark areas. In this respect they are somewhat similar to young lava flow units. Both units are found down slope from river valleys which flow onto the coastal plain. This suggests they may be laharic in origin.

Circular Features in the Tertiary Volcanic Belt of Guatemala

During preparation of the photolineation map (Figure 2) we noticed a distinct concentration of circular and arcuate structural elements within the volcanic belt of Guatemala. We used the S190B photographs to prepare a separate map of these features (Figure 5). A few of the features mapped (labeled by name on the map) are Quaternary cones and domes. To the north of this WNW-trending line of Quaternary volcanoes, correlating with the extent of Tertiary volcanic rocks, is the area where the greatest density of arcuate and circular features (mainly topographic depressions) are found. Their shapes and the close association of these features with the volcanic belt suggests a volcanic origin. We believe they represent Tertiary volcanic centers.

The Tertiary volcanic belt in Guatemala is not well described and very little is known about the volcanoes which produced these rocks. Existing descriptions (Williams, 1960; Bonis, 1965; Lamarre and others, 1971) seem to emphasize the flat-lying character of Tertiary rock units and suggest fissure vent origin for the eruptions. This style of volcanism contrasts with Quaternary events, which seem to center on steep, composite cones. The description of this contrast is made less certain by the recognition (McBirney, 1975) that volcanism is episodic in Central America and a significant period of quiescence separates the Quaternary activity from Tertiary volcanism. This means that erosion has had a much longer time to obscure Tertiary volcanic features.

Nonetheless, circular volcanic features within the Tertiary of Guatemala have been recognized before, west of Sansur in the San José Pinula Quadrangle (Lamarre and others, 1971). These probably represent eroded Tertiary cones and/or caldera-like structures. In Figure 5, the abundance of these circular structures increased to the southeast, from Volcán Tacaná to Quezaltenango. This change correlates with a general change in lithology within the Tertiary, from a dominance of basaltic andesite flows in southwestern Guatemala (Bonis, 1965) to more siliceous ash flow dominance within the central Guatemalan Highlands (Williams, 1960). Thus, the circular features may be more particularly associated with siliceous volcanism. We believe the map also suggests that the number of circular features may be

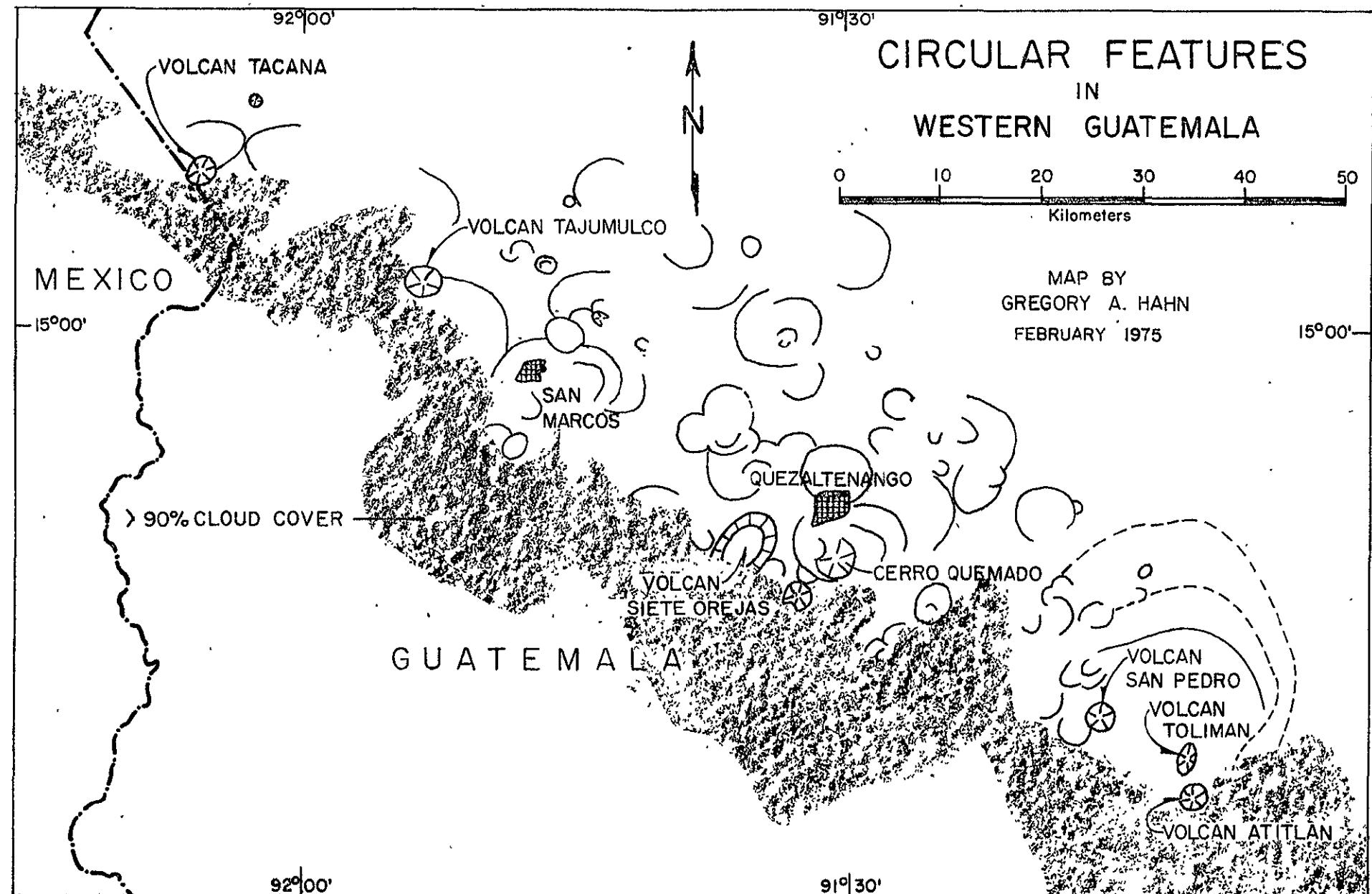


Figure 5: Map of arcuate and circular features within the western volcanic highlands of Guatemala. Prepared from S190B color photographs.

most abundant around the proposed boundary of the segmented Benioff Zone that passes northeastward through Quezaltenango. This suggestion must be corroborated by other examples before we can say whether these proposed transverse structural elements have significance in the Tertiary record.

CONCLUSIONS

1. S190 photographs proved a useful basis for structural mapping in northern Central America, permitting the delineation of a high density of photolineations, and the recognition of circular features.

2. The structural geology of northwestern Central America, and to some degree of the remainder of the volcanic chain is dominated by NW trending faults. These structures parallel and are related to the active seismic zone, but are not well understood in detail.

3. NE-trending faults are also of general importance all along the volcanic axis of Central America. In Guatemala, concentrations of NE-trending faults occur in areas where transverse segmentation of the volcanic chain and the seismic zone have been postulated.

4. The Polochic fault system "horsetails" into a complex series of faults, striking NW to SW, westward of the Mexican border. The plate boundary, which seems so well defined in western Guatemala, consists of a whole system of shears in southern Chiapas.

5. The Tertiary volcanic province of Guatemala is characterized by an abundance of circular structural features, which reflect old volcanic centers. The existence of these underlines a fundamental difference in the style of volcanism in the Tertiary and Quaternary.

ACKNOWLEDGEMENTS

Financial support for this work came from NASA contract NAS-9-13311. Peter Ostlender drafted all maps and figures.

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TECHNICAL RESULTS

B. The cooling of Izalco Volcano (El Salvador)
1964-1974 by R. E. Stoiber, W. I. Rose, Jr.,
I. M. Lange and R. W. Birnie.

Publication of the report:

1. Geologisches Jahrbuch, Hanover B. 13, 1975
(in press).
2. Smithsonian Inst. Center for Short-Lived
Phenomena, Event 21-74, Card 1792 (1974).

The Cooling of Izalco Volcano, 1964-1974

Richard E. Stoiber¹
William L. Rose, Jr.²
Ian M. Lange³
Richard W. Birnie¹

Abstract

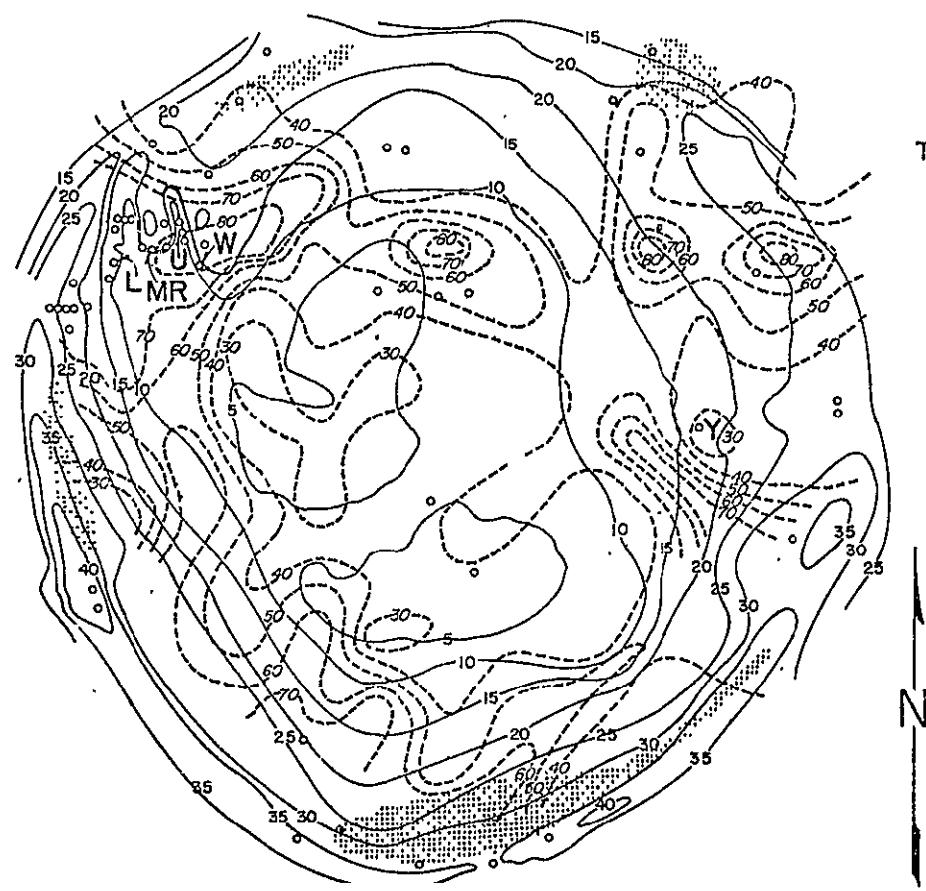
Ground surveys on more than 65 different dates 1964-1974, show that Izalco's summit crater fumaroles have steadily cooled at constant but different rates since the last eruption in 1966. The cooling trend is affected by the alternating rainy and dry seasons of El Salvador. Recent radiometer surveys have further quantified the magnitude of the seasonal temperature fluctuation. All of the temperature information, supplemented by geochemical and gravity observations give no evidence that Izalco, once the most regularly active vent in Central America, is about to resume activity.

- 1) Dept. of Earth Sciences, Dartmouth College, Hanover, N.H. 03755
- 2) Dept. of Geology & Geological Engineering, Michigan Technological University, Houghton, Michigan 49931
- 3) Dept. of Geology, University of Montana, Missoula, Montana 59801

Introduction

So continuously active during the period from its birth in 1770 until 1958, that is assumed the title of "lighthouse of the Pacific", Izalco has been nearly completely in repose since the latter date. Only a brief, very small flank eruption in 1966 has interrupted the dormancy. The extrusion of a small ($900,000 \text{ m}^3$) lava flow from a vent 550 m below the summit had remarkable little effect on the summit area, and Strombolian activity, in the past a hallmark of Izalco, was completely absent. Details of this eruption are contained in a previous article (Rose and Stoiber, 1969). Since 1964 temperatures of the fumaroles in the summit crater of Izalco have been measured periodically, and a variety of other observations have been made irregularly. This report is written to summarize these measurements and observations.

Izalco is a small composite cone, representing a total volume of about 2 km^3 . It is composed of basalt of rather uniform composition (Rose and Stoiber, 1969, p. 3124). The summit crater has been of interest to the authors because of the existence of several high temperature volcanic fumaroles (Figure 1). These fumaroles have been thoroughly studied geochemically mainly by the sampling of gas condensates (Stoiber and Rose, 1970), and mineral incrustations around the fumarole openings (Stoiber and Rose, 1974). Part of the interest of these geochemical studies has been the examination of variations with time, since for many years it has been apparent that the crater was cooling. In general, as the temperatures have decreased the geochemistry of the gaseous emanations have become more and more nearly completely dominated by H_2O , finally containing barely detectable



IZALCO SUMMIT CRATER
EL SALVADOR C.A.
TOPOGRAPHIC AND TEMPERATURE MAP

0 20 meter 40

SYMBOLS:

- FUMAROLE
- TOPOGRAPHIC CONTOUR (INTERVAL = 5 m)
BASE ELEVATION TAKEN AT CRATER
- - - ISOTHERM IN °CELSIUS (INTERVAL = 10°)
- AREA ENCLOSING MANY STEAM VENTS

DATES OF SURVEY:

TOPOGRAPHY: FEBRUARY 1964

TEMPERATURE: NOVEMBER 1965

Figure 1: A topographic map of the summit crater of Izalco showing relative elevations (the elevation of the highest point is listed as 1965 m by local maps), and the location of fumaroles. The fumaroles studied intensively are labeled. Superimposed on the topography are found temperature isotherms, based on temperatures taken 10 cm below the surface on a 15 m grid in November 1965 by Dennis Eberl.

concentrations of acid gases. During the same period the variety of incrustations depositing around the fumaroles has decreased markedly also.

Fumarole Temperature Measurements

Figure 2 shows the cooling curves of the five Izalco fumaroles. As far as we know, this is the most extensive data available on the temperature changes of volcanic fumaroles with time. Four of these five vents (U, W, MR and L) are found very close to each other (within 20 m) on the inner slope of the summit crater's SW rim. One of the fumaroles (Y), is located on the other side of the crater about 130 meters from the others (Figure 1). There are almost 100 other fumaroles in the crater, but all are lower temperature and less prolific than the five which were monitored. In 1965 a temperature survey (Figure 1) showed a pattern of heat connecting the two hottest areas within the crater.

Plots such as those shown can be used to determine cooling rates for the fumaroles. For all the fumaroles, nearly linear trends can be inferred from the plots of Figure 2, particularly so if only the period following the 1966 eruption is considered. As was reported earlier (Rose and Stoiber, 1969), the cooling rates for the fumaroles increased after the 1966 eruption, possibly reflecting the depletion of the magma storage by the lava flow. Reexamination of the cooling curves after the accumulation of six more years of data generally reinforces our conclusions; however, one of the five fumaroles (L) is cooling at a markedly slower rate than the others. Table 1 shows a tabulation of the cooling rates of the five fumaroles since the 1966 eruption.

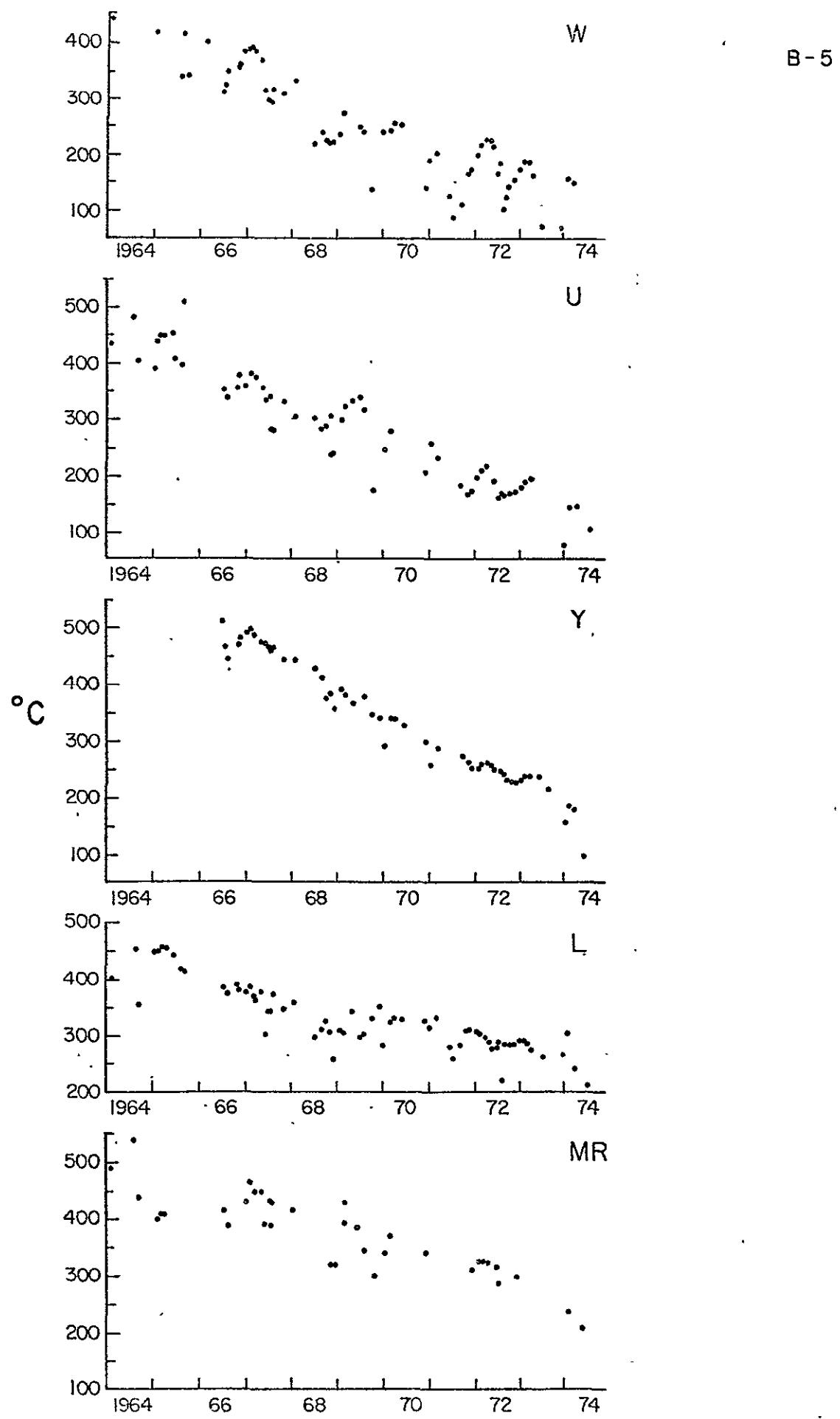


Figure 2: Time-Temperature plots for Izalco summit crater fumaroles.

Table 1

Cooling Rates of Izalco Crater Fumaroles 1967-74 .

<u>Fumarole</u>	<u>°C/Yr</u>
W	45
Y	45
MR	28
U	34
L	14

The linearity of these curves, especially the curves for Y, W, and L, can be improved somewhat if semilog plots are used, but are judged to be sufficiently linear without such plots to be an adequate representation. Since the trends are so nearly linear, there is no evidence of any change in the heat source for these gas vents in the eight years since the eruption.

The explanation of the differences in cooling rates of the fumaroles probably arises from a combination of two factors: 1) size and proximity of the heat source and 2) the degree of meteoric water infiltration affecting each of the fumaroles. We can make some geologic judgements of both factors. Although we do not know the distance from the surface to the heat source, we could reasonably expect that the fumarole Y which is on the inner eastern slope of the crater, would be most adversely affected by magma withdrawal from an eruption on the southeast flank of the cone. Thus the higher cooling rate of Y may be related to the position of the fumarole. This factor cannot fully explain the other differences observed, in the other fumaroles which are so closely spaced. The degree of meteoric infiltration can be qualitatively evaluated by estimating the drop in fumarole temperature which is associated with the well-defined rainy season that occurs between May and November. Figure 3 shows some examples of this effect and Table 2 shows some estimates of the magnitude of these drops in years where control was sufficiently good. It is clear that fumarole W is much more responsive to the rainy season than L or Y. The differences shown in the table probably reflect differences in the degree of infiltration of groundwater. Fumaroles like W, for example, are cooled more rapidly because groundwater has better access to the conduit of the fumarole between the source and the surface.

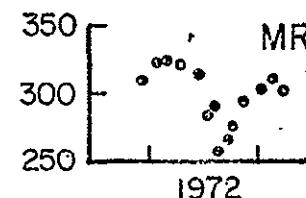
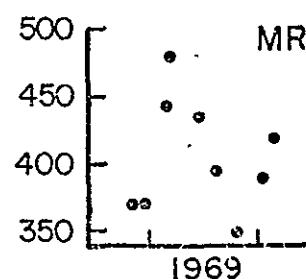
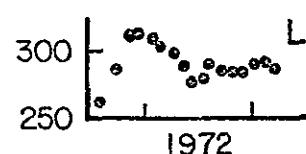
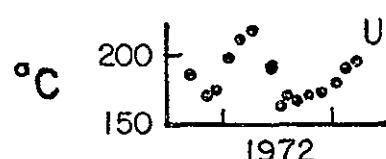
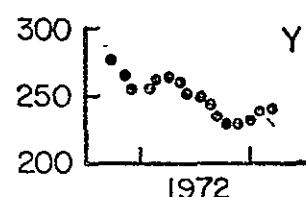
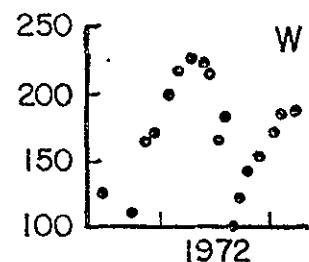
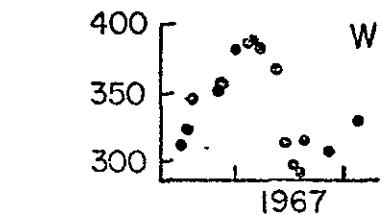


Figure 3: Details of Figure 2 showing the differing magnitude of seasonal temperature damping by rainfall on Izalco fumaroles.

Table 2

Magnitude of Seasonal Rainfall Damping of Fumarole Temperatures

<u>Fumarole</u>	<u>Year</u>	<u>Estimated Magnitude (nearest 10°)</u>
W	1967	90°
W	1972	120°
MR	1969	80°
MR	1972	70°
U	1972	50°
L	1972	30°
Y	1972	20°

In summary the fumarole temperature data documents a steady cooling of the interior of the Izalco cone, without detectable perturbations or rate changes since 1966. Different fumaroles have different cooling rates due to both differences in the size and proximity of the source and differences in the degree of groundwater infiltration.

Infrared Thermal Measurements

Infrared thermal patterns have been measured on the northeast flank of Izalco seven times since December 1969. A Barnes PRT-5 radiation thermometer was used to measure apparent surface temperatures. The radiation thermometer was set up on Cerro Verde, a small cone on the south flank of Santa Ana Volcano and about 1200 m in direct line from Izalco. The patterns are measured in the early morning hours before the sun strikes the mountain. In this manner the anomalies can be attributed to geothermal heat and not differential solar heating.

The radiation thermometer employed in the 16 December, 1969 and 3 April, 1970 studies measured the intensity of the radiant emittance in the 8-14 μ band integrated over a 2° field of view (Birnie, 1971). This field of view translates to a circular area on the surface of Izalco of about 36 m in diameter. No anomalies were noted in these patterns. This is attributed to the large field of view of the radiation thermometer which may mask a small, but intense thermal anomaly.

Commencing in July, 1973 a new Barnes PRT-5 radiation thermometer was employed which measures the radiant emittance in the 9.5 - 11.5 μ band

with a 0.14° field of view, thereby reducing the circular area over which the apparent surface temperature is integrated to approximately 3 m.

Figures 4-8 show the thermal patterns measured in the following days: 7 July, 1973, 24 November, 1973, 16 February, 1974, 28 April, 1974, and 1 December, 1974. It should be emphasized that the isotherms in the patterns are apparent temperatures not corrected for the effects of atmospheric absorption of infrared radiation or the nonunity of surface emissivity. For comparative purposes, apparent temperatures are considered sufficient. The details of corrections for the effects of atmospheric absorption and surface emissivity are discussed by Birnie (1973). Approximately 250 m of relief are present in Figures 4-8.

On the 7 July, 1973 pattern (Figure 4), a thermal anomaly is clearly present just below the summit crater rim. The anomaly is located in a zone of low temperature fumaroles which have been present since at least 1964. The anomaly stretches down slope about 50 m and covers an area approximately 1000 m^2 . The highest of the anomalous apparent surface temperatures is 15°C , 2°C above ambient. Thermal data measured on 24 November, 1973 (Figure 5) show the anomaly expanded to the east covering about 5000 m^2 . The maximum apparent surface temperature occurs in the same region as the July, 1973 anomaly (Figure 4) but is now 19°C , 8°C above ambient.

The 16 February, 1974 data (Figure 6) show the anomaly still present. The maximum apparent temperatures are again 19°C , 8°C above ambient; and the anomaly covers much the same area as in November, 1973 (Figure 5). On 28 April, 1974 (Figure 7), the anomaly is present though the maximum

vary antithetically with rainfall, but the fumarole temperatures appear to respond to the seasonal change with a several month time lag. Part of this lag may be explained by the later arrival of the rainy season in the year 1972 (when fumarole data for Figure 9 were taken) than in 1974 (when the radiation surveys were taken). But in addition it is probable that downward percolating rain water takes more time to cool the fumarole temperature, while their effect on the surface is immediate.

We conclude that trends in surface temperatures of volcanoes must be carefully analyzed in light of possible seasonal variations before long term changes in the geothermal regimes of the volcanoes can be assumed.

Other Observations

Some other observations are relevant regarding the possibilities of renewed eruption at Izalco. 1) Concentrations of many chemical species (including Cl, SO_4 , F, Ca, Mg, Na and K) in condensates sampled from Izalco fumaroles have steadily decreased (Figure 10), until many are barely detectable. The Cl/ SO_4 ratios in condensates have been high, greater than 100, while studies have shown that fumaroles associated with active vents have Cl/ SO_4 ratios of one or less. 2) Microearthquake activity, measured by Wood (1974), in 1972 is very low when compared with other potentially active vents in Central America. Microearthquake activity at Izalco is currently being continually monitored (Ward and others, 1974), and has not increased significantly at latest report (Ward, P. L. pers. comm.).

3) Table 3 shows the results of repeated gravity surveys at three stations

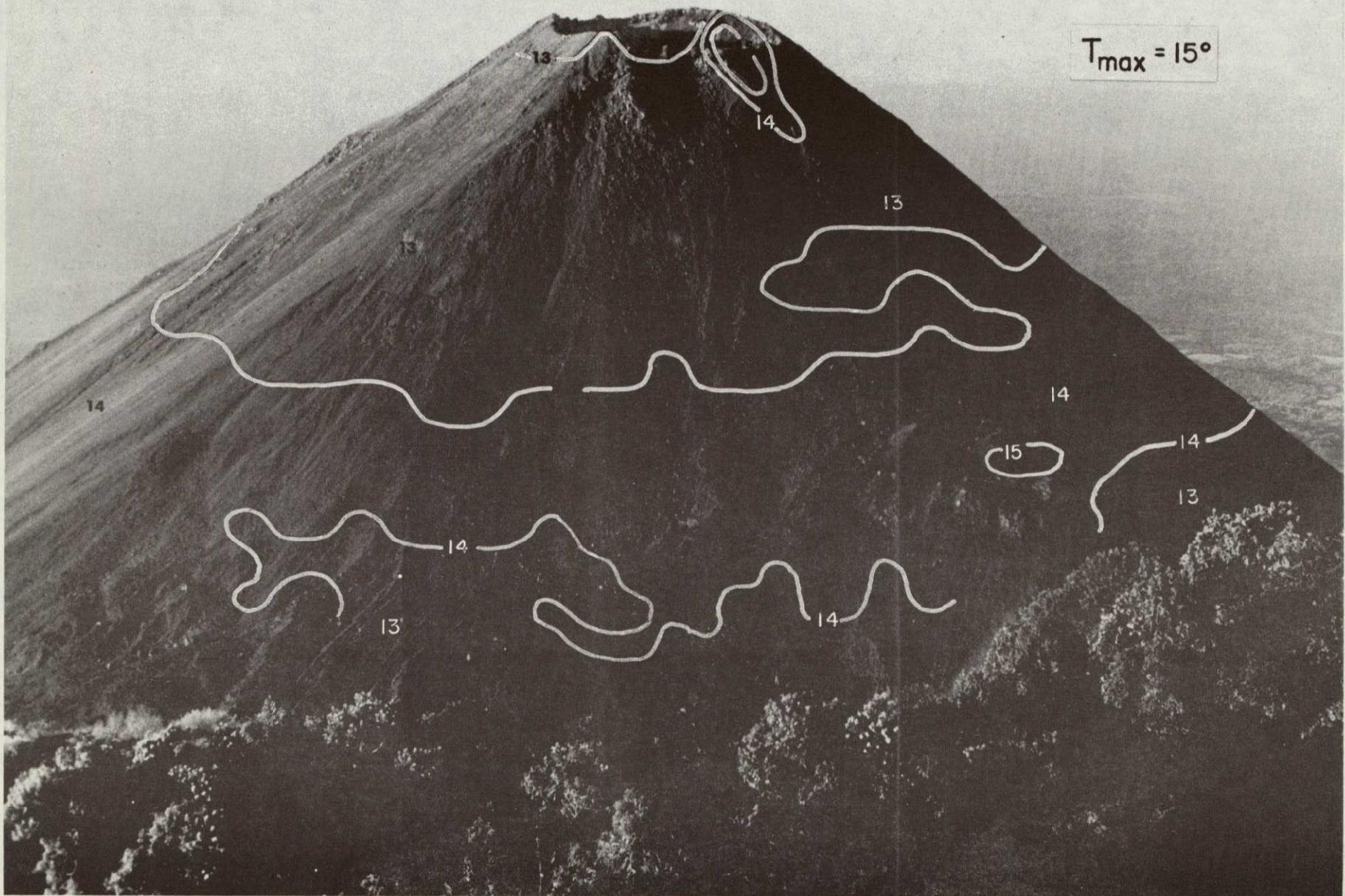


Figure 4: Isotherms of apparent surface temperatures in $^{\circ}\text{C}$ on the northeast flank of Izalco Volcano July 7, 1973. The maximum apparent surface temperatures in the hottest parts of the patterns near the crater rim are indicated on the photo.

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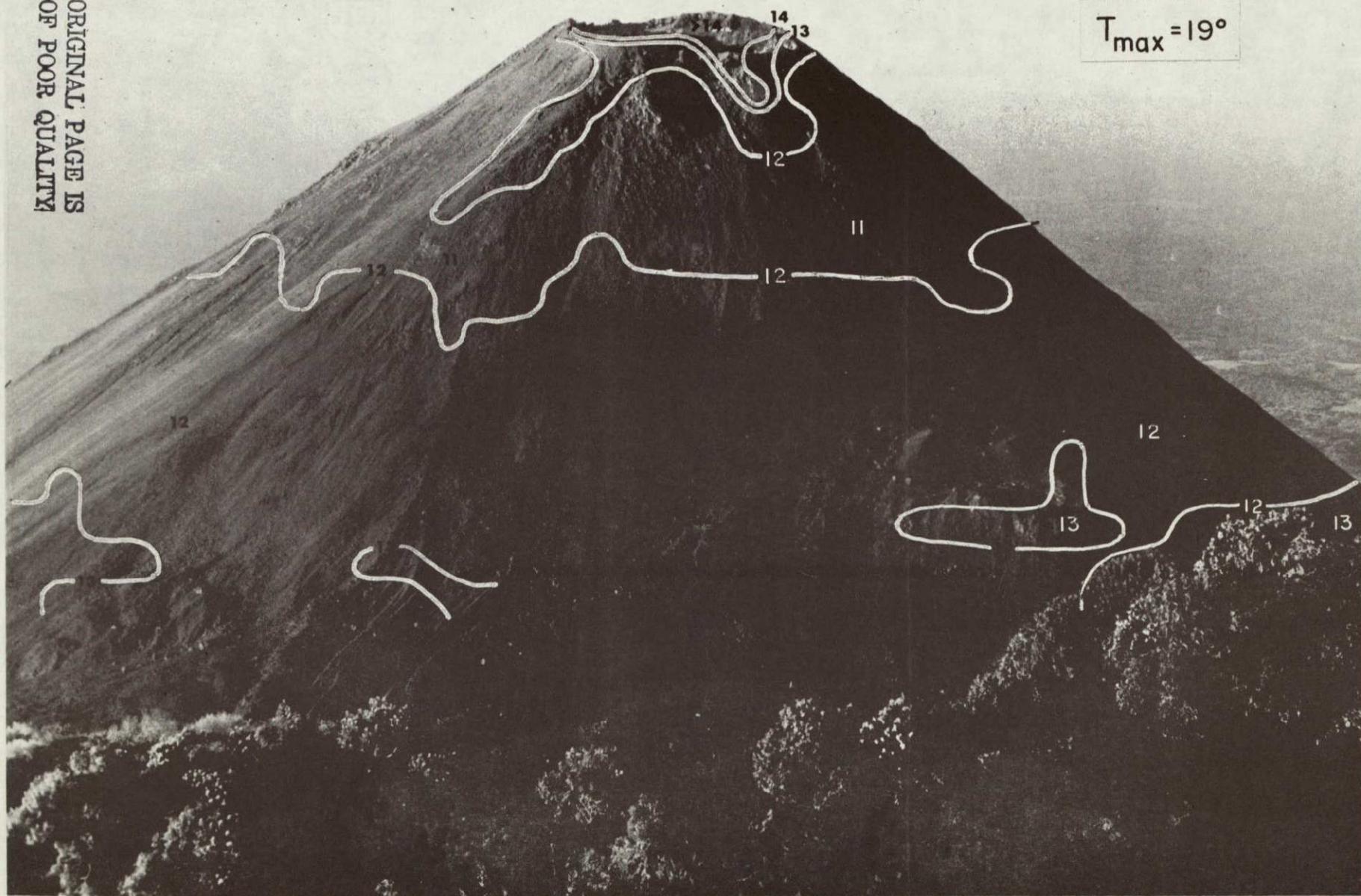


Figure 5: Isotherms of apparent surface temperature determined on November 24, 1973.

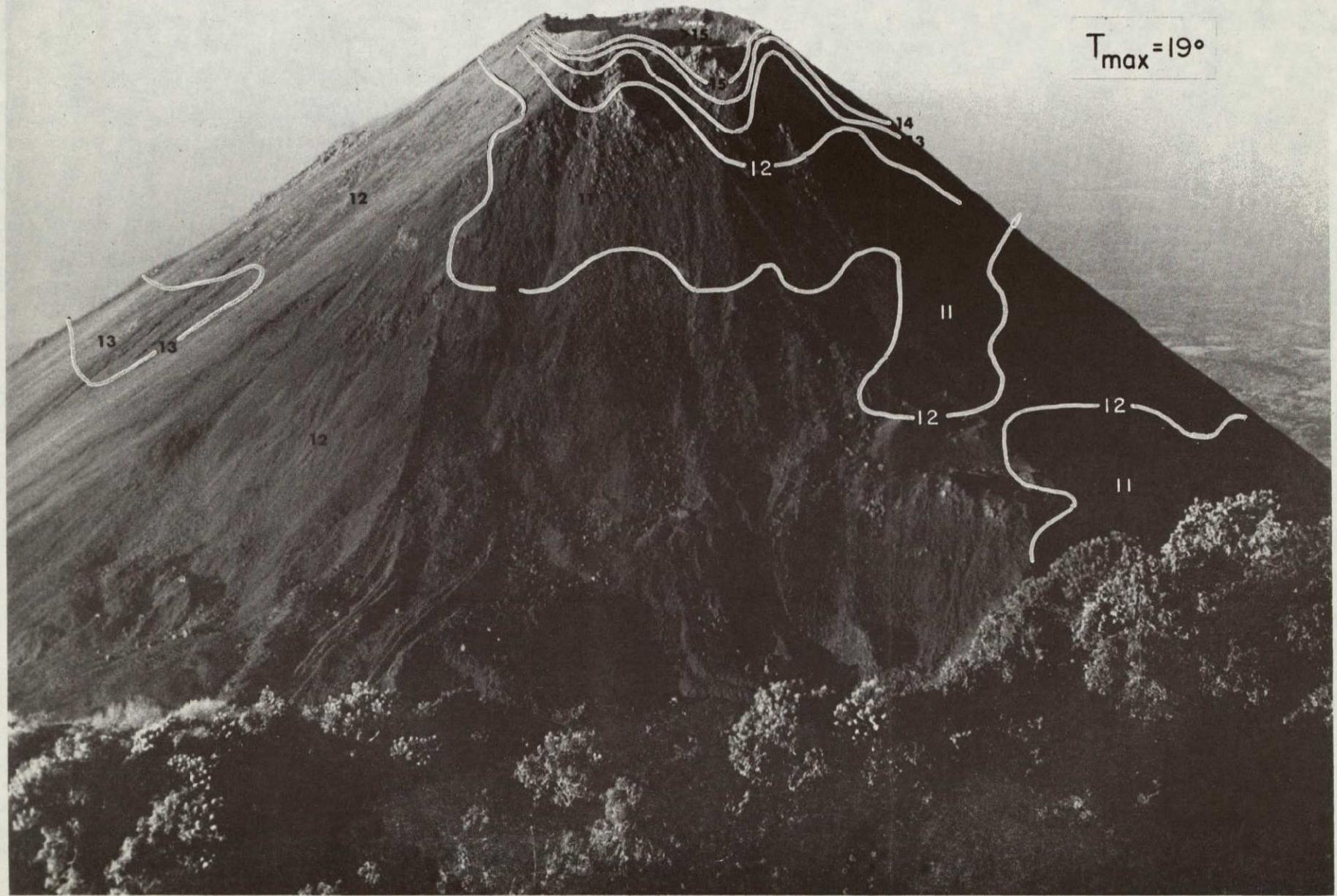


Figure 6: Isotherms of apparent surface temperature determined on February 16, 1974.

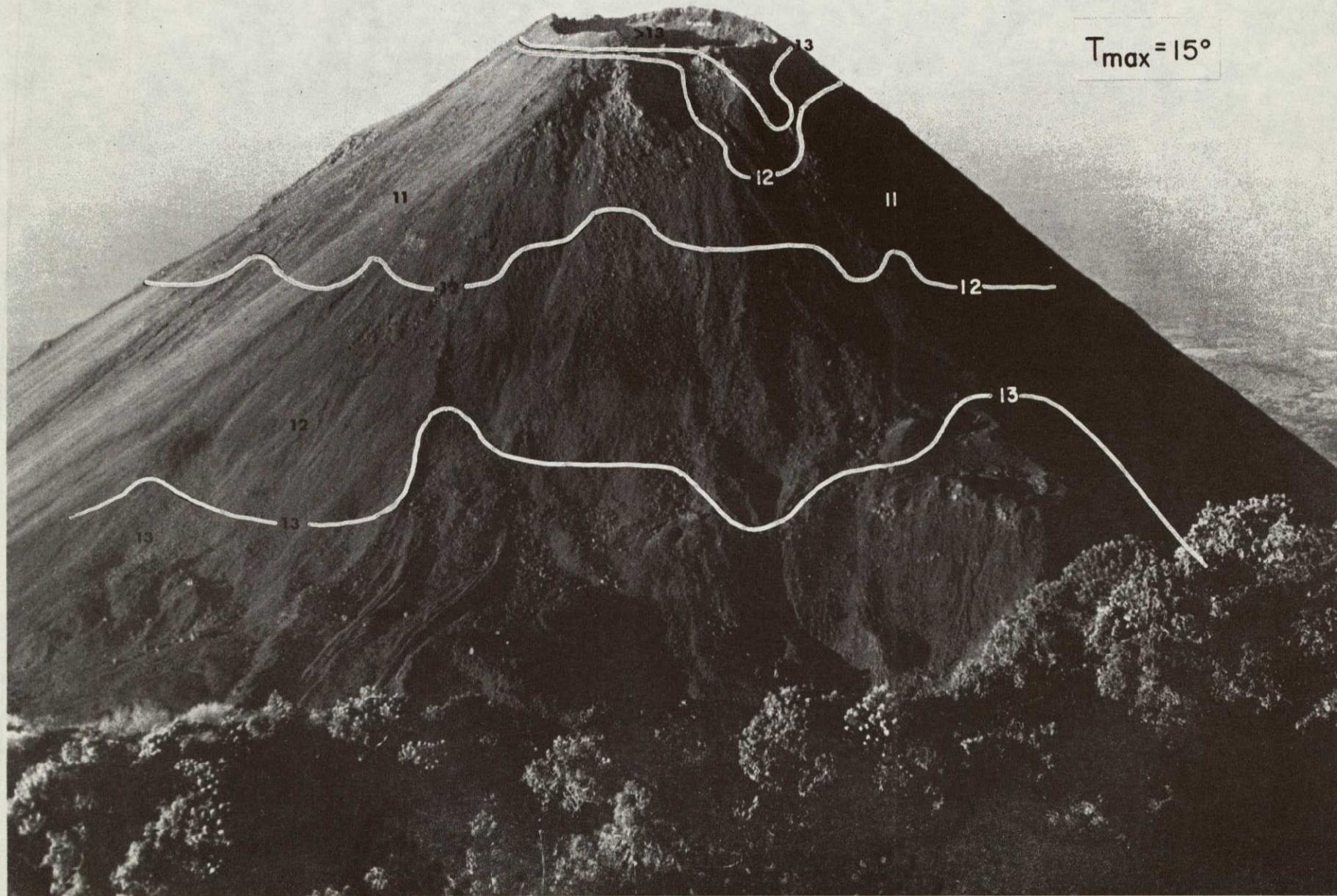


Figure 7: Isotherms of apparent surface temperature determined on April 28, 1974.



Figure 8: Isotherms of apparent surface temperature determined on December 1, 1974.

temperatures are reduced to 4°C above ambient. The anomaly is contracted to an area of about 3000 m². By 1 December, 1974 (Figure 8), the apparent temperatures increase again and have maximum apparent temperatures 7°C. above ambient. This later survey shows a slight shifting of the zone of maximum temperatures to the east; but in general, the anomaly covers the same general area as the November, 1973 (Figure 5), and February, 1974 (Figure 8) surveys.

Figure 9 plots the change in intensity of the thermal anomaly with time. Following the November, 1973 pattern (Birnie et al., 1973), it was felt that the increase in intensity may be due to an upward movement of magma and, therefore, be telegraphing an impending eruption. However, reference to Figure 9 clearly indicates that the anomaly leveled off, fell in the spring of 1974, and rose again in December 1974. The average monthly rainfall is also plotted on Figure 9. The relationship between the intensity of the thermal anomaly and the amount of rainfall is clearly antithetic. During the dry season, there is a limited amount of removal of geothermal heat at the surface by the latent heat of evaporation of rain. The surfaces, therefore, appear hotter to the infrared thermal sensor during the dry season.

The temperature of fumaroles at Izalco has also been noted to undergo seasonal changes (see Figure 3). The seasonal variation of temperature of W fumarole at Izalco is plotted on Figure 9. Though the fumarole temperatures are plotted for the years 1971-72 and the surface temperatures are for 1973-74, the comparison is considered realistic because the average annual rainfall data vary little from year to year. The fumarole temperatures also

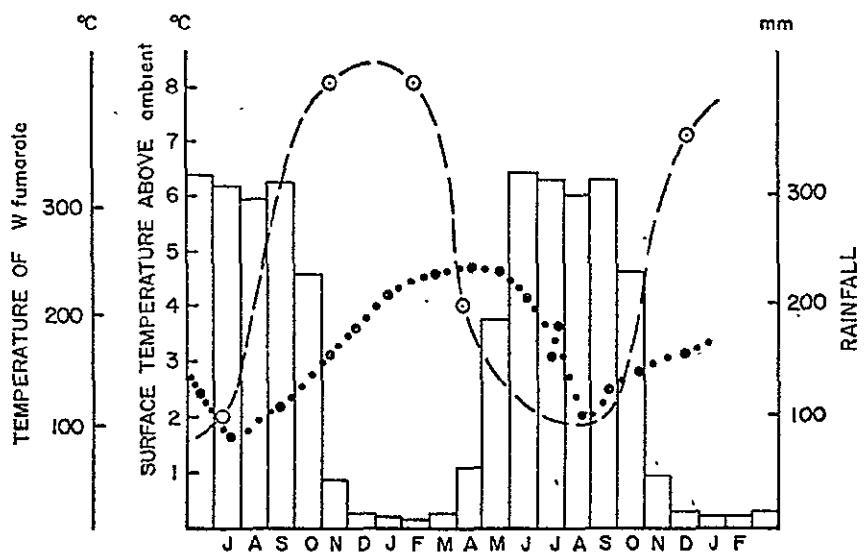


Figure 9: Plots of the temperature above ambient of the surface thermal anomaly on the Izalco cone as compiled from data of Figures 4-8 (dashed line); the temperature of W fumarole, 1971-72 (from Figure 3, dotted line) and the average monthly rainfall for San Salvador (histogram). Source of rainfall data is Servicio Meteorologico Nacional (1967).

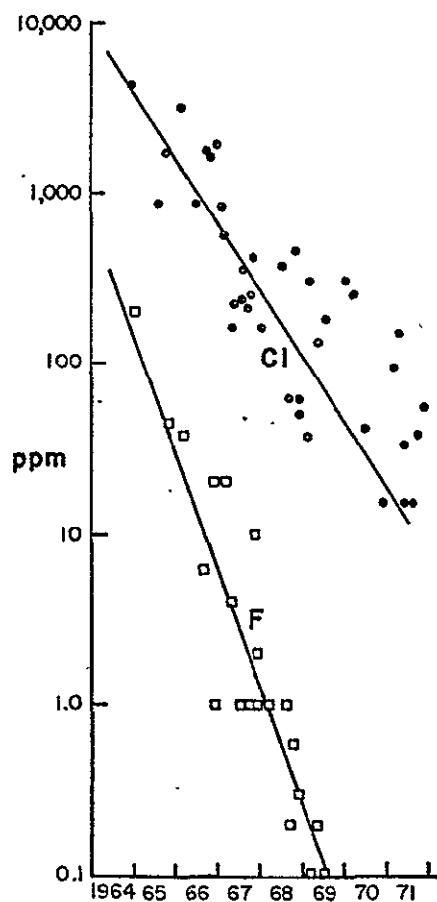


Figure 10: Plot showing change in concentration of Cl and F in condensates from W fumarole, Izalco, from 1965-1972. (Other components have analogous relationships, see Stoiber and Rose, 1970 for pre-1970 data).

Table 3: Gravimetric measurements, Izalco Volcano, El Salvador. All values in milligals, standardized to Station 3.

Station	Location	Distance from center of crater km	14 Aug. 64	4 Jul. 66	22 Nov. 66	15 Aug. 67	18 Nov. 67	12 Nov. 68	9 Dec. 69	6 Dec. 70	5 Dec. 71	14-16 Oct. 72*	30 Nov. 72**	27 Apr. 74	
1	San Salvador	56	--	362.8	362.6	362.3	--	362.9	363.1	362.5	363.1	362.8	363.0	362.7	0.26
2	Cerro Verde	1.3	48.7	48.6	48.8	48.6	--	--	48.4	48.2	48.9	48.6	47.9	48.5	0.29
3	Finca las Brumas	2.2	100.	100.	100.	100.	100.	--***	100.	100.	100.	100.	100.	100.	--
4	N. Base of cone	0.6	154.1	153.9	154.6	154.1	155.5	154.3	154.2	154.2	154.5	154.1	154.3	154.1	0.42
5	N. rim of crater, E. side	0.1	58.3	58.7	59.0	58.6	59.0	58.2	57.9	58.4	58.9	58.7	58.7	58.3	0.37
6	Bottom of crater, E. side	0.07	61.6	61.1	61.7	61.4	61.9	61.7	61.2	61.5	61.6	61.4	61.6	61.3	0.22
7	Lowest point in crater	0.04	66.9	66.4	67.0	66.7	67.3	66.8	66.5	66.8	67.1	66.7	66.8	66.5	0.27

*Ave. of three surveys

**Ave. of two surveys

***This data set normalized to 154.3 for station #4 (mean)

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on the cone, and four stations off the cone itself, at various distances from the summit crater. The standard deviations of values taken at stations on the cone are the same as those taken at various distances. We do not know if detectable gravity changes would or should occur as an antecedent to an eruption, but in all these surveys, spanning ten years, no significant relative gravity changes are found. 4) The variety of incrustations occurring around fumarolic openings has decreased markedly during the ten year period. A large number of mineral phases, including rare species like Scherbinite (V_2O_5) (see Stoiber and Rose, 1974, for details), were found in the period 1962-1967, but in recent years the incrustation suite is simplified to small amounts of anhydrite, gypsum and chloraluminate.

In spite of a variety of measurements, both geochemical and geo-physical, with many done repeatedly, Izalco is not yet showing any signs of revival of activity. We hope that temperature measurements of fumaroles in Izalco's crater can be made regularly enough in the future to determine if fumarole temperature changes will forecast impending activity.

Acknowledgements

Financial support for visiting Izalco has come from the American Philosophical Society (1964), the National Science Foundation (Grants GP-4861, GA-1533, and GA-26026) and the National Aeronautics and Space Administration (Contract NAS 9-13311).

The government of El Salvador has generously provided logistical help through the Centro de Estudios e Investigaciones Geotecnicas (Ing. Edgar Parker) and the Compania Electrica del Rio Lempa (Ing. Armando Vides).

In particular we thank several individuals who repeatedly helped collect data, which always means climbing the volcano: Moises Harrouch, Arturo Marroquin, Dennis Eberl, Samuel Bonis and Hector Recinos. In addition, Eberl compiled the data necessary to assemble the thermal map of the crater (Figure 2).

The PRT-5 radiation thermometer was purchased following receipt of a grant from the Research Corporation.

Tom Crafford, Glen Johns, Lindsay McClelland, Holt Ardrey, and Greg Hahn aided in collecting the infrared thermal data.

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TECHNICAL RESULTS

C. Nue  ardente from Santiaguito Volcano, April
1973, by W. I. Rose, Jr.

Publication of the report:

1. Bulletin Volcanologique, T. 37, pp. 365-371
(1973).

Nu   Ardente from Santiaguito Volcano
April 1973

W. I. Rose, Jr.
Department of Geology and Geological Engineering
Michigan Technological University
Houghton, Michigan 49931 USA

ABSTRACT

The largest nu   ardente eruption of Santiaguito since November 1929, occurred April 19, 1973. The nu   descended the valley of the Rio Nima II for a distance of about 4 km. The ash flow itself was restricted to the river bed, but the hot gas cloud devastated an area of more than 3 square kilometers extending hundreds of meters on both sides of the river bed. Because the ash cloud stopped about 2 km from the nearest habitations, there were no fatalities.

Introduction

During the night of April 19, 1973, Santiaguito volcano produced its largest *nueée ardente* in 40 years. The eruption occurred on a cloudy night so no direct visual observations were reported from inhabited areas. By far the dominant recollection of inhabitants at plantations 7 km south of Santiaguito was a nearly unbearable SO_2 gas odor, which was accompanied by steady rumbling. Ash fell in areas to the west and south of Santiaguito, the maximum reported thickness of new ash was 10 cm.

Field Observation

Some details of the eruption can be reconstructed from field examination of the area affected. The eruption came from the Caliente vent, which occupies a position in about the center of the 1902 explosion crater of Santa María and which has been the principal pyroclastic vent throughout all of Santiaguito's 51 year history of activity. An ash flow descended the southeast flank of Santiaguito and entered the valley of a tributary of the Río Nima II. This tributary has (since the 1950's) been draining the 1902 crater of Santa María, until mid-1972, when a lava flow from the Caliente vent reclosed the crater. After entering the river valley, the ash flow simply followed the steep-walled canyons downstream for a distance of about 4 km, to a point below the Mirador of La Florida. At this point the ash flow material is still more than 2 km from the nearest habitation, the finca La Florida. The ash flow itself was restricted to the river channel, which is nowhere wider than about 20 meters. Near the La Florida mirador, the ash flow material was constricted in a band of the

channel, and accumulations of hot material was still producing secondary steam explosions more than two months after the eruption. Such explosions are quite a common feature of ash flow activity; they were well described by ANDERSON and FLETT (1903) at St. Vincent. They occur when hot ash in the river bed is invaded by river water. Local reports that this emission was due to the opening of a new crater are erroneous.

The most dramatic effects of the eruption occurred on the slopes of the Rio Nima II drainage system above the river bed itself. Here a large area, more than 100 times the area of the ash flow itself, was devastated by the glowing cloud above the ash flow. The devastation provides an especially dramatic contrast since the local vegetation is very dense jungle. The area affected is about three square kilometers (Figure 1). Within the outlined area all green vegetation was destroyed. Near the river bed all trees were flattened, broken off at ground level, with the trunks (up to 1 m in diameter) either pointing in the direction of flow or transported away (Figure 2). Moving uphill away from the river valley toward the margins of the affected area, the intensity of the blast was obviously lessened, with some trees remaining upright. At the edges of the devastated zone many trees were upright; this was especially true where the forest was topographically shielded from the force of the blast (in the lee of a ridge). The boundaries of the devastated area were surprisingly abrupt, typically a transition zone of only a few meters was found, beyond which the vegetation was still verdant. The width of the devastated zone decreased in the downstream direction, apparently because the eruption dissipated as it moved.

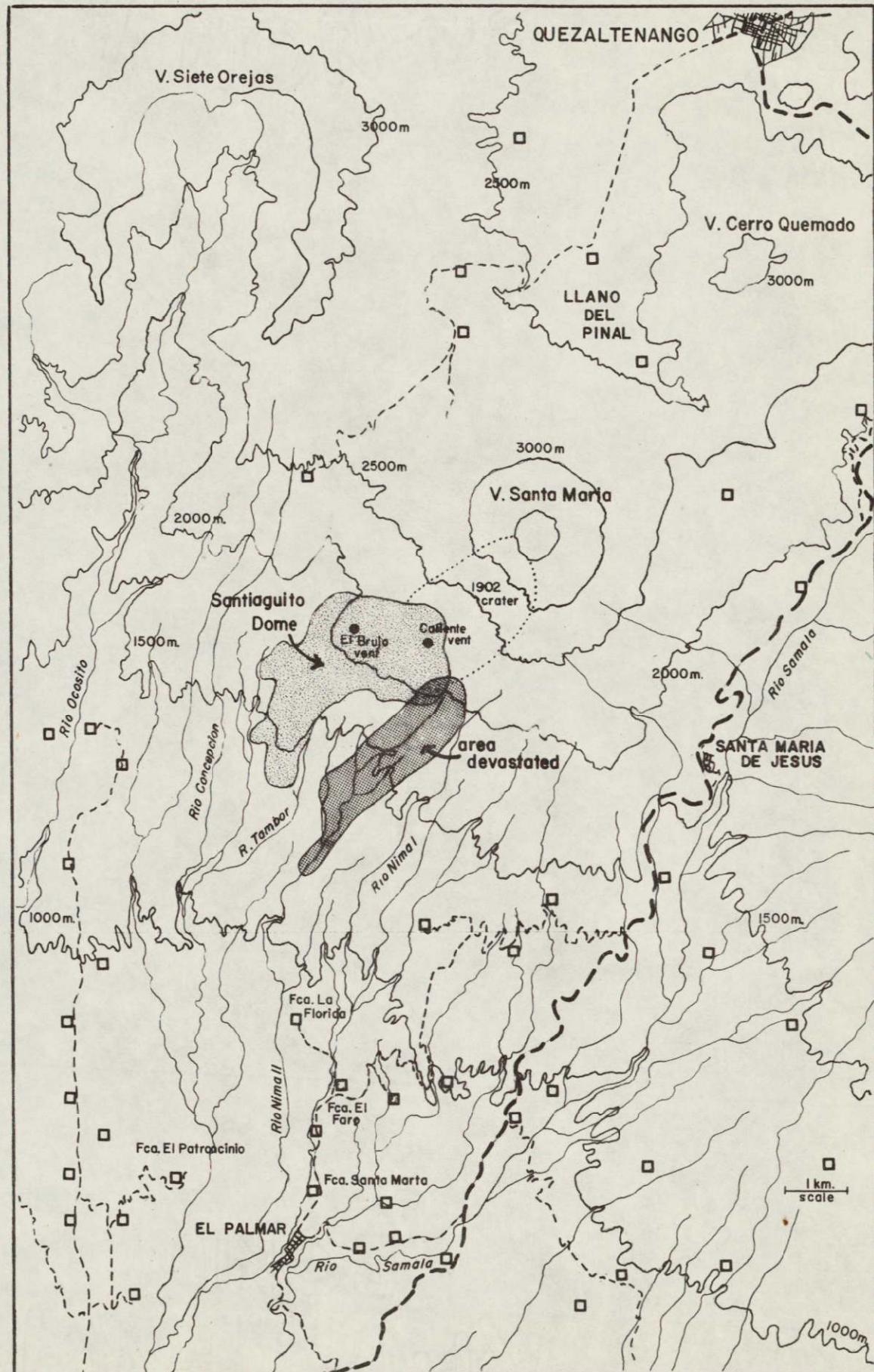


Figure 1 - Map showing the extent of the area effected by the April 1973 nuee ardente. Squares symbolize inhabited locations. North is to the top, contour interval is 500 meters. Base maps obtained from Instituto Geográfico Nacional, Guatemala City.



Figure 2: Photograph showing devastation of forest just inside the edge of the affected zone of Figure 1. Trees as large as 1 m in diameter were denuded and broken off, their trunks all pointing in the direction of movement of the nuée (to the left in the photo).

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The only event of Santiaguito's eruptive history which has a similarity to this April, 1973 eruption, was the great *nueée* of November, 1929, which killed several hundred people (SAPPER and TERMER, 1930). Even though Santiaguito has produced many *nueée ardente* eruptions, particularly in the periods of 1923-25, 1929-33 and 1967-68 (ROSE, 1973), except for the November, 1929 blast, events did not have devastating "hurricane cloud" zones in anything approaching the proportions of the April, 1973 event.

It would seem desirable as well as practical, to pay particular attention to the relative scales of the areas affected by 1) the ash flow deposit itself and 2) the turbulent hot gas blast cloud or "hurricane" cloud. Many events which are reported as "*nueée ardentes*" have a gas wave outside of the ash flow which has very limited proportions, often affecting less area than the ash flow deposit itself. Such events are quite different from what happened at Santiaguito in April, 1973.

Within the devastated zone the thickness of eruptive material deposited on the ground was minimal -- at most only a few centimeters. The material is powdered dacite, with very poor sorting and many fragments of 5 cm or more in diameter. This material was transported by a hurricane force gas cloud. The density of the cloud allowed it to effect damage which could only be produced by even higher velocity winds, if no suspended rock chips were involved. Heat effects inside the devastated area were interesting. Again there was a gradation from the river bed toward the borders, with burned tree trunks common near the valley, and with only baking or singeing effects near the margins. It is thus clear that most of the area was not subjected to temperatures much in excess

of about 200°C, though the rock chips transported by the gas blast may have been hotter, retaining their heat in proportion to their size.

Discussion of many of the same characteristics can be found in TAYLOR (1958) who detailed the effects of Mt. Lamington's great eruption in 1951. That event had a much larger devastated zone (200 km^2 vs 3 km^2) and produced far more pyroclastic material, but otherwise was very much like the recent Santiaguito blast.

Discussion

The occurrence of this kind of dangerous eruptive event is obviously of great environmental importance to the coastal slope of Guatemala below Santiaguito. The eruption of November 1929, was of a similar type, but extended at least 2 km farther from the dome and affected the valleys of the Río Tambor and Río Concepcion (to the west) as well as the Río Nima II. It is the same area that would now be affected if a larger eruption should occur. The closest inhabited site that would be affected is Finca La Florida.

Other areas near the valleys of the Tambor and Nima II (Finca El Patroncinio, Finca Santa Marta and the town of El Palmar) are much farther away, but would still be expected to be in some danger if another eruption came. As one moves farther downstream the danger would be more apt to be from mudflows than from ash flow or hot gas clouds. Since none of the inhabited areas are directly within the river bed, most of the danger to the populace would seem to be from the hurricane cloud effects. TAYLOR (1958, p. 49) has indicated that it seems most likely that the principal cause of death in the case of the Lamington event was not the temperature within the cloud or

poisonous gases inhaled, but hot dust which was inhaled. People in the open were killed, those in well-closed rooms survived. It would seem that a simple gas mask would afford an extra edge of protection from hot ash inhalation, and that these masks might be a useful safety investment at least for people living at the finca La Florida. People who would not have time to evacuate the area might have time to reach a conveniently placed gas mask and some kind of closed shelter. A small, inexpensive lightweight gas mask could be carried in the pocket by those working far from shelter.

It is impossible to know whether another such event is likely in the near future. But little about the character of activity at Santiaguito has changed since early 1970. Blocky lava flows are still being extruded from both the Caliente vent and the El Brujo vent, 2 km to the west. The Caliente vent is still obstructed by a large lava plug -- no obvious crater was created by the April eruption. A large gaseous plume is still being emitted through the blocky plug dome at the Caliente vent, as was the case for two years before the April, 1973 eruption. During lava flow activity at other lateral vents, nūées with very limited gas clouds have been observed (STOIBER and ROSE, 1969), but nūées with large "hurricane" clouds are only produced when lava flows are being extruded from the Caliente vent. The significance of this fact with respect to the mechanism of volcanic activity at Santiaguito is obscure -- it is only an empirical observation. There was a two-year repose interval between the last Caliente pyroclastic activity and the April, 1973 eruption. This is judged to have little predictive significance based on past activity in Santiaguito.

Perhaps most significantly, no sign of any more pyroclastic activity or nūées from the Caliente vent has occurred in more than 2-1/2 months since

April 19. A report of some activity on June 7, is almost certainly false. Only small, very frequent incandescent rockfall activity down the east and southeast slopes of the Caliente dome has been observed, indicative that the blocky flow is still active. One other facet of the current activity may have some significance ultimately to local residents. The newest blocky flow from Caliente vent has dammed the 1902 crater at the east end, as mentioned above. A lake is forming now in the crater, as was the case in 1902-22 and probably in the 1940's. If this lake should fill to the level of the dam, a catastrophic overflow which would breach the dam is possible. Such overflow would almost certainly produce a mudflow which would descend the Rio Nima II and possibly the Rio Tambor. This event could occur without an eruption and suggests that the crater lake should be observed periodically to know if any likelihood of such an event exists.

Acknowledgements

Financial support for this investigation came from the National Aeronautics and Space Administration of the United States (NAS 9-13311). Vehicular support was provided by the Government of Guatemala through the Instituto Geografico Nacional.

Roland LaForge and Samuel Bonis aided in collecting information. The kindness of personnel of the Finca El Faro is also greatly appreciated.

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TECHNICAL RESULTS

D. Nue  ardente from the foot of a dacite lava
flow, Santiaguito Volcano, by S. B. Bonis and
W. I. Rose, Jr.

1. Submitted for publication to Geology, July 1975.
2. Smithsonian Inst. Center for Short-Lived Phenomena,
Event 117-73, Cards 1711, 1714 (1973).

Nuée ardente eruption from the foot of a dacite
lava flow, Santiaguito Volcano, Guatemala

Samuel B. Bonis
División Geológica
Instituto Geográfico Nacional
GUATEMALA, C.A.

William I. Rose, Jr.
Department of Geology and Geological Engineering
Michigan Technological University
Houghton, Michigan 49931
USA

Abstract

Field observations of the zone affected by a small nuée ardente which issued from Santiaguito volcanic dome on 15 September 1973, have established clearly that the eruption came from the distal end of a blocky dacite lava flow. This emphasizes that such eruptions need not be related to an underground magma storage.

Scanning electron microscopy of the ash from the nuée deposit reveals highly vesicular particles with ruptured surface vesicles. This supports hypotheses that employ active vesiculation as part of the mechanism of movement for some nuée ardentes.

Introduction

Reports of prominent pyroclastic activity at Santiaguito were heard from many sources in western Guatemala on 16 September 1973 (El Gráfico, Guatemala City, 17 September 1973). These reports described an ash column which reached 8000 m upward and very loud explosions. The eruption was apparently a short-lived event beginning at about 7:20 a.m. local time and lasting only a few minutes. Explosions were heard 15 km away. Ash fell at great distances from Santiaguito being scattered mainly in a WNW direction for distances of 50 km or so. A muddy rain shower was caused at Colombá, 14 km west of the volcano. At 10:30 a.m. mudflows reached the Río Tambor at about 9 km downstream from the dome. Since there are no nearby inhabitants, there was no awareness of an ash flow until an expedition reached the affected area three days after the eruption. No human deaths or material damage took place as a result of the activity. One of our observation team, which has

been monitoring the Santiaguito dome for the last 12 years, was on the dome at the time of the eruption. He was about 1.5 km east and uphill of the source. Although out of sight of the actual event, he did see the high ash cloud which emerged silently and noted subsequent lightning which caused the loud explosions reported at a distance.

Santiaguito is a multiple extrusive volcanic dome which has been continuously active since 1922 (Rose, 1973a). It has been mapped and described in detail (Rose, 1972) and has been regularly visited and observed in recent years.

Field Observations

From speaking with an observer and local residents, it became clear that this eruption, unlike most pyroclastic activity at Santiaguito, was associated with the western part of the dome complex, called El Brujo (Figure 1). When the valley of the Río Concepción was visited on 19 September, the ashflow deposit and "hurricane cloud zone" showed clearly that a *nueé ardente* had occurred, flowing about 3 km down the river valley toward the coastal plain. In this direction, but several kilometers farther south, are inhabited areas. The path of the *nueé* is shown in Figure 1, which also shows comparative observations of an April *nueé*. Both the distances of travel and the areas of devastation resulting from the two *nueés* are similar, the September event slightly smaller by both measures. The character of devastation was also similar (see Rose, 1973b). Within the devastated zone a thin (generally less than 15 cm, up to 1 meter in places) deposit of ash was found, and the vegetation was completely destroyed, both by the heat of the ash and gas of the cloud, and by the hurricane force wind which propelled them. Both the thickness of ash and

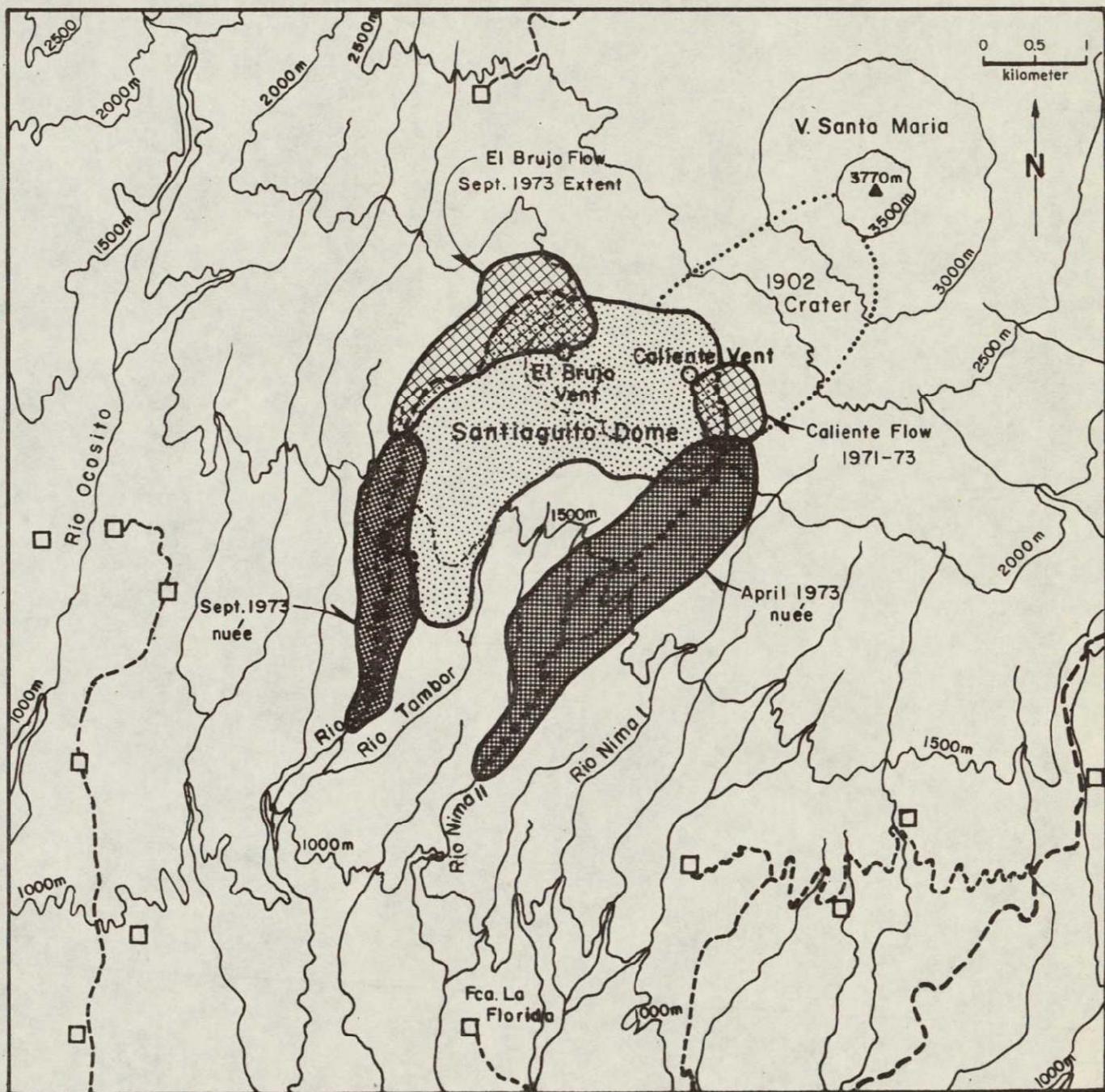


Figure 1 - Map showing areas devastated by nuées ardentes of April and September 1973 at Santiaguito. Squares represent inhabited areas.

the degree of devastation increased toward the valley bottom, where the bedload itself was mainly restricted to the stream bottom. The area covered by the bedload avalanche deposit itself was probably only about 1% of the devastated zone. The bouldery bedload is an unbedded, completely unsorted unit, with blocks up to 4 meters set in an ash matrix. Thickness of this deposit was as much as 5 meters. The devastated area is illustrated and described by the photographs and captions in Figures 2-10, taken three days after the eruption.

The most significant observation made concerning the eruption was that the source could be so well established as the foot of the lava flow. The nuée issued from the lobe of a thick blocky lava flow, at a point two kilometers from the flow vent and more than 3 kilometers from the principal vent of Santiaguito (Caliente vent). As the river valley is sloping sharply toward the coastal plain, and no traces of the ash flow and ash fall deposit could be observed uphill from the flow front, we feel sure that the pronounced avalanche scar at the terminus of the flow was the source (Figure 11). In addition we know from previous observation that part of the flow front had disappeared. At this site, the source of the nuée, there is no sign of underlying feeder or fissure. This means that the nuée eruption was produced entirely from a magma body on the surface. The fact that ash flows can occur without a subsurface feeder system may not be widely recognized. It appears that the ash flow occurred as a result of oversteepening of the flow front which triggered an unusually large avalanche; that in turn exposed a large hot vesiculating lava surface, from which the nuée erupted.



Figure 2 - The bed of the Río Concepción 750 m from the nuée source. The bouldery unsorted bedload deposit of the eruption fills the valley and is up to at least 5 m in thickness. The bedload material is not found outside of the riverbed itself.

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Figure 3 - View southward along the Río Concepción about 500 m south of the nuée source. The bed of the Río Concepción is on the extreme left of the photo. The photograph exemplifies the most severe devastation effects of the hurricane cloud zone. Trees and shrubs are broken off and a deposit of ash and lapilli, carried by the hurricane cloud, forms a 20-50 cm deposit. The "bed load" deposit of the nuée, restricted to the river channel, is much thicker and includes much larger volcanic debris (see Figure 8).



Figure 4 - Detail of standing tree trunk within the devastated zone. The sand-blasting effects of the hurricane cloud are clearly shown, causing the bark to be stripped and the wood to be charred, both effects restricted to one side (right in the photo), the direction from which the nuée traveled. The trunks shown are 25 cm in diameter.



Figure 5 - Splintered tree trunk within the devastated zone, diameter 30 cm. Note strongly directed fabric of trunk splinters and reeds, depicting the flow direction of the hurricane cloud. Many trees were broken off at levels significantly (repeatedly about 2 m) above the top of the ash deposit. From this we infer that the effects of the hurricane cloud reached at least 3 m above former ground level (see also Figure 2). We are unsure how much settling of the deposit has taken place.



Figure 6 - Within the hurricane cloud zone about 500 m from the source vent, but in the lee of a small ridge (the Concepción valley is to the left). Some trees remain upright, though completely stripped of leaves.



Figure 7 - The Río Concepción valley 200 meters from the nuee source. Just beyond the standing man is the river bed, in which the bed load deposit is steaming, due to infiltration of rainwater from rill systems formed in the ash and lapilli deposits. Small steamy fumaroles depositing sulfate incrustations were active. Traces of the previous vegetation are almost completely absent, but can be seen on the horizon.

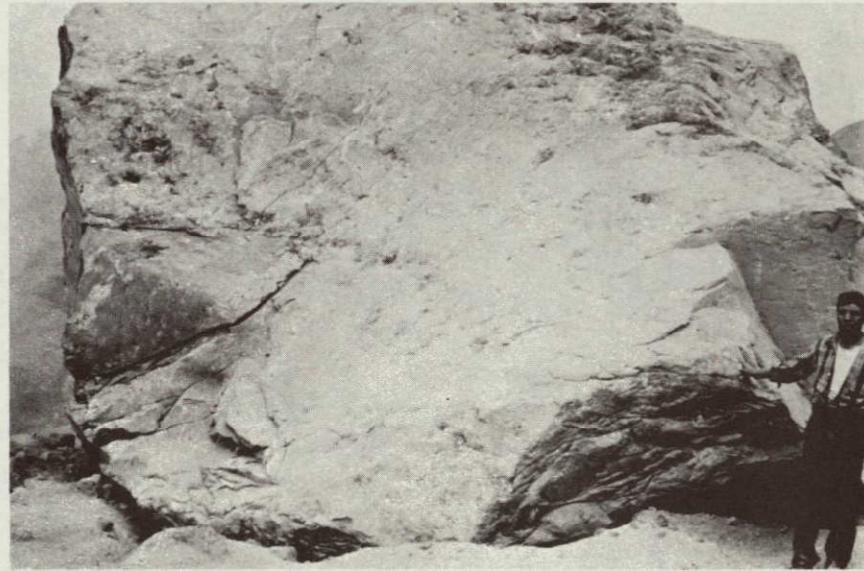


Figure 8 - Within the bed of the Río Concepción, showing one of the largest boulders carried along the bed of the stream. The boulder is dacite, derived from the lava flow near the source. The bouldery unsorted bed deposit extended for 3 kilometers along the Río Concepción. Large boulders like this were carried about 1 km downstream from the source.



Figure 9 - Three kilometers downstream from the source of the nuée where the hurricane cloud zone, peripheral to the river bed, ends. The photo taken in the river bed, shows steep erosional walls primarily a result of running water erosion prior to the nuée. Some scouring of the walls by the nuée was observed, however. In the distance trees are upright and retain some leaves, particularly on the highest branches. Closer to the river bed the devastation becomes steadily more severe. The transition zone from strongly devastated area to only minor effects was comparatively narrow (30-50 m). Downstream from this point the devastation was minor or absent.

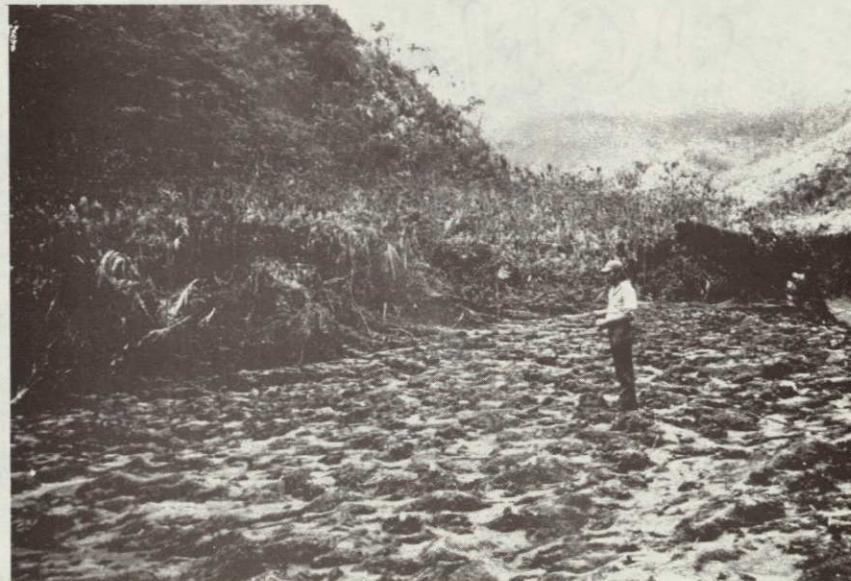


Figure 10 - At the distal end of the nuée bed load deposit, where it has evolved into a mudflow. Three and a half kilometers downstream from the source, the marginal devastated zone is absent, and only localized heat effects are noted on the vegetation along the river banks. The mudflow, wet ash and lapilli material with some boulders and cobbles, continued down the river for several kilometers.

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Figure 11 - Aerial photograph taken on 3 October 1973, by Instituto Geográfico Nacional, Guatemala. The terminus of the El Brujo lava flow is clearly shown, and the light-colored avalanche scar at the flow front is the source of the September nuée.

There was formerly a hot spring within the valley somewhere near where the nuée source was located. We do not judge this to have significance, but we report it for completeness.

The lava flow from which the nuée issued began forming in early 1972, after a small plug dome was extruded in December 1971 (Figure 12). All of the activity in 1973 was concentrated at the southwest lobe, which was following the Rio Concepcion valley. Since the nuée of September 1973, this lava flow has continued advancing to the southwest. In the months of November and December 1973, a number of avalanches and very small nuées (up to 200 m long) were observed during expeditions to the flow front. The flow was still advancing as of April 1975, but no large nuées have occurred except the September 1973 event.

Chemistry of the eruption products

The newly erupted nuée materials are almost identical in chemical composition to both the April nuée deposits and all of the previously erupted Santiaguito lavas (Table 1). The ashes produced are being studied in textural and chemical detail, as part of a series of fresh pyroclastic materials from several recent Central American eruptions.

Types, Causes and Mechanisms of Nuée Ardentes

Attempts to classify types of nuée ardentes according to their origin have been enlightening. That of MacDonald (1972, p. 152) is summarized in Table 2. In the light of the most recent Santiaguito nuée the justification for separating "explosively generated" nuées from those associated with "dome or flow collapse" is obscure. It is unquestionable that the 8000 m high ash cloud and extensive hurricane blast was due to an explosive event, and

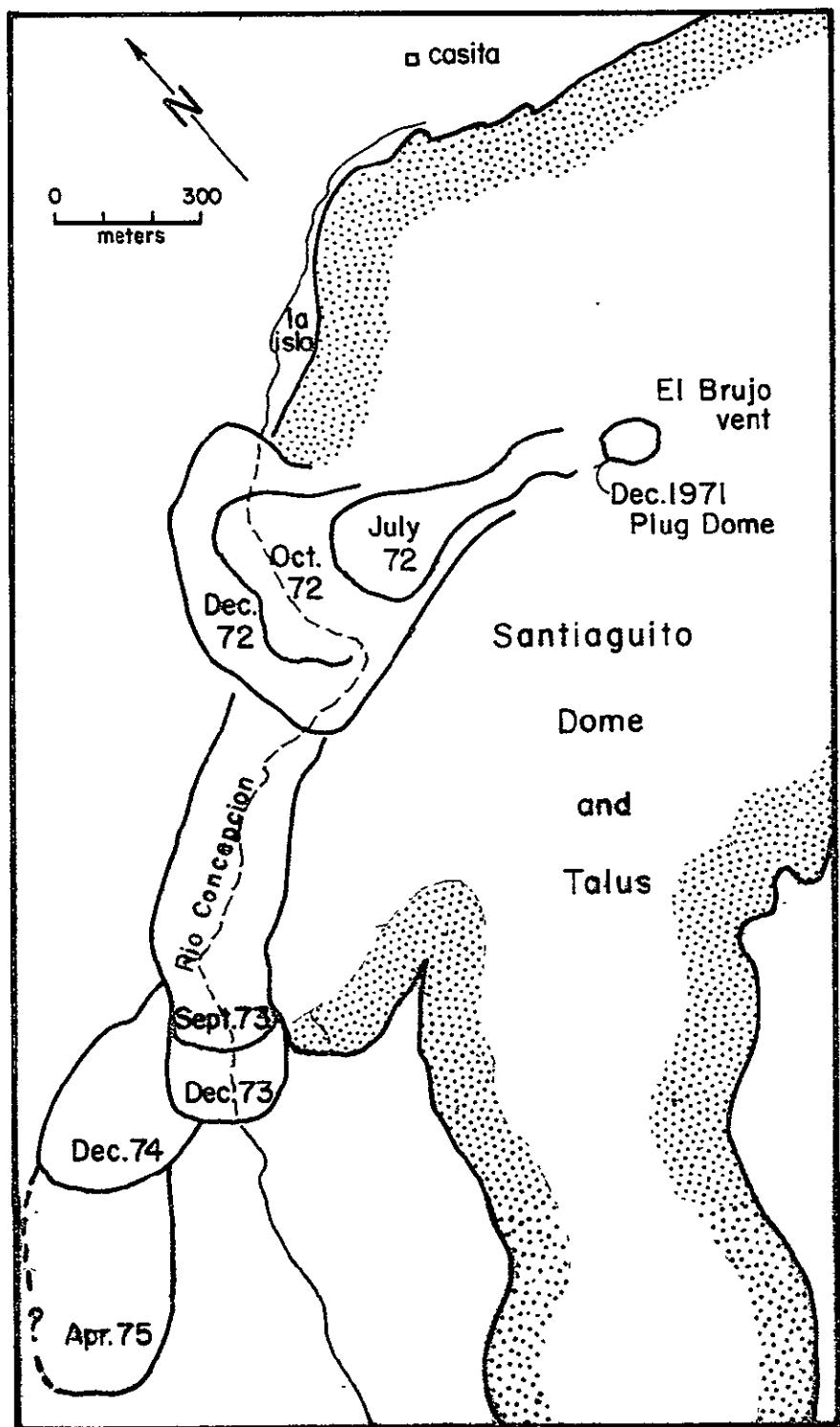


Figure 12: Map showing the growth of the most recent lava flow from the El Brujo vent at various dates.

Table 1

Chemistry of 1973 nuée ardente materials from
Santiaguito Volcano, Guatemala

	1	2	3
SiO ₂	63.0	63.8	63.45
Al ₂ O ₃	16.4	15.2	16.94
Fe ₂ O ₃ *	5.9	5.2	5.08
MgO	1.7	2.2	1.87
CaO	5.1	4.3	5.03
Na ₂ O	4.5	4.7	4.91
K ₂ O	1.6	1.6	1.59
TiO ₂	0.5	0.5	0.47
H ₂ O	0.4	0.5	0.29
Total	99.1	98.0	99.99**

*Total Fe as Fe₂O₃

1. Lapilli from April 1973 nuée deposit, analysis by XRF and AAS rapid techniques, W. I. Rose, Jr.
2. Lapilli from September 1973 nuée deposit (analysis as in No. 1)
3. Average of 19 previous analyses of Santiaguito dome rock (Rose, 1972, p. 1421)

**Total includes 0.22% P₂O₅ and 0.14% MnO.

Table 2

Types of nuée ardentes (after MacDonald, 1972)

<u>Type</u>	<u>Type Example</u>
1. Explosively Generated	
A. Vertical explosion with fall-back	Soufriere, 1902
B. Low angle explosion	Peleé, 1902
2. Dome (or flow) collapse	Merapi, 1930
3. Hot ash accumulation on steep slopes	Vesuvius, 1906

yet it is also clear that the eruption was associated with the crumbling of the flow front. Collapse of a hot dome or lava flow can evidently trigger an explosion, perhaps by exposing an area of hotter lava to the surface. In particular nuée Type 1B is, therefore, difficult to distinguish from Type 2. If a body of magma on the surface, as the dome at Mt. Pelée, is capable of initiating explosions (Perret, 1937), it is not surprising that such events could sometimes be triggered by oversteeping of ponderous domal masses of viscous lava flows.

There is controversy among observers of nuée ardente eruptions and their effects as to the cause of movement. As ably summarized by MacDonald (1972, p. 152), some investigators, particularly those who have observed nuées associated with volcanic domes, like Mt. Pelée (Lacroix, 1904; Perret, 1937) and Mt. Lamington (Taylor, 1958) have emphasized the continual vesiculation and degassing of ash particles during the transport of the nuée as important in the mobility of the ash flow. Such vesiculation was actually observed in a large block transported by a nuée from the dome at the Hibokhibok (MacDonald, 1972, p. 5). Others, apparently chiefly those observers who have seen nuées associated with composite cones of more mafic composition like Mt. Mayon (Moore and Melson, 1969), Ulawun Volcano (Johnson, et. al., 1972) and Volcán Arenal (Melson and Saenz, 1973) have emphasized that the mobility of nuées is due chiefly to the entrapment and heating of cold air beneath and within the avalanche, following the suggestions of McTaggart (1960).

We examined the ash of the nuée deposit carefully to characterize the particles. In particular, if vesiculation is occurring during nuée transport, then vesicular particles are likely, perhaps even particles which show ruptured surface vesicles (see Muenow, 1973,

p. 1558). For examination of the surface textures, scanning electron microscopy was used (Figures 13 and 14). Fine sand size fractions of the ash were selected for ease of study. Most sand size particles observed in the ash were angular (Figure 13), consisting of broken crystals and rock fragments. A small percentage (1-5%) of sand size grains were extremely vesicular, however, and showed ruptured surface vesicles (Figure 14). These vesicular particles are extremely fragile networks of thin silicate glass (pumicious), and it seems probable that they are greatly underrepresented in the fine sand size which was examined in detail, and that the finer size fractions include higher proportions of vesicular glassy material due to the widespread rupturing of vesicles. Since the lava flow from which the nuée erupted does not show vesicularity to this degree or at this scale, it seems safe to conclude that vesiculation took place during the eruption of the nuée. We plan to examine samples of the ash of this nuée along with samples of several other recent nuées in Central America in greater detail.

If some nuées are actively vesiculating, while others are not, differences in their characteristics should be evident. One possible characteristic that would vary would be the relative sizes of the "bed load" deposit of the nuée (which usually is restricted within a stream channel) and the devastated zone which was affected by the hurricane wind. A few maps exist which allow such a comparison. There is a broad range in the ratios of the area of bedload/area devastated, from a low of about 1:1 to a high of more than 1:100. Both Santaguito events (Figure 1) have values nearer the latter, as does the great 1902 Mt. Pelée nuée (MacDonald, 1972, p. 144). Nuée events observed at Mt. Ulawun (Johnson, et. al.,



.03cm

Figure 13: Scanning electron microscope image of ash of the September nuée ardente. This sample was size sorted prior to imagery. Note the general angularity of ash particles. Most particles shown are broken crystals, vesicular particles are rare. The vesiculated groundmass of the lava is mostly in the finer size fractions.

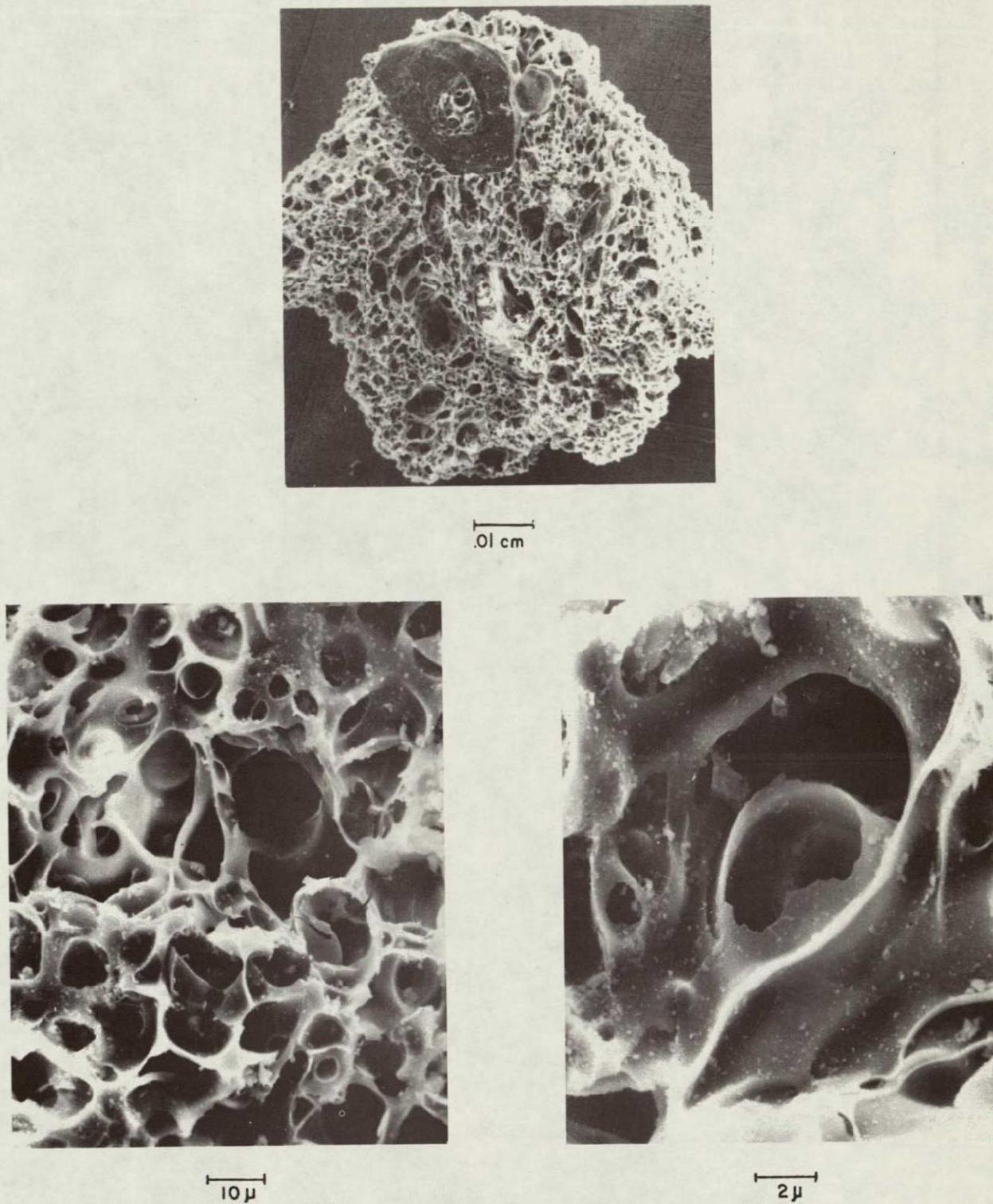


Figure 14: Three SEM images of a highly vesicular ash particle in the same ash sample of the nuée bed load shown in Figure 13. Note the extreme vesiculation and the thinness of the vesicle walls. On the right, at the highest magnification a ruptured surface vesicle is shown. Such particles make up only a small fraction of the coarser splits of the ash, but because of their delicate character are more abundant in the finer fractions.

1972, p. 19) and Mt. Mayon (Moore and Melson, 1969, p. 602) appear to have ratios of about 1:5. Whether this difference indicates that vesiculation was less important in the latter eruptions is not known, but it is a possibility meriting consideration.

Acknowledgements

Financial support for the observation of Santiaguito's activity during 1973 came from the National Aeronautics and Space Administration through contract NAS 9-13311 and from the National Science Foundation through Grant GA-26026. The Instituto Geográfico Nacional provided financial and logistical support through Oscar D. Salazar.

Indispensible field assistance was provided by Pedro Pérez López. Sonny Knight gave essential help in the scanning electron microscope laboratory.

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